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Technical Report
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MOORING DESIGN AND INSPECTION CRITERIA

by

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EXECUTIVE SUMMARY

The State of California is in the process of reviewing and formulating various design and inspection criteria for waterfront facilities. The Naval Facilities Engineering Command (NFESC) was invited to provide input, due to the U.S. Navy's experience and expertise.

In this report various commercial criteria are compared to MIL-HDBL-1026/4 "Mooring Design" (draft of 1998) and recommendations are made. This manual was designed for all classes of ships, including tankers. The State of California may want to consider adopting or incorporating this manual into their criteria.

Mooring analyses tools, a U.S. Navy ships' database, a climate database and a facilities database are being designed to work with MIL-HDBK-1026/4. This will allow the user to quickly and easily perform computations with a minimum of input. The State of California may wish to participate in development of these items.

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1.0 INTRODUCTION

It is vitally important that ships remain safely moored when in port. A single accident can result in tens or hundreds of millions of dollars in cost, disastrous environmental problems and a potentially huge loss of life. Proper mooring design, construction, inspection and operation can fortunately minimize the possibility of accidents. Fortunately, the cost of proper facilities is only a tiny fraction, for example, of the cost of a single ship and great progress has been made in recent years in improving safety. For example, computer methods and understanding of mooring technology have improved design methods. At the same time many years of practical experience and successful operation provide valuable insight.

In order to provide safe facilities, the California State Land Commission is in progress of reviewing facility design and inspection criteria for waterfront facilities. The goal of this review is to develop a comprehensive set of commercial standards.

The Naval Facilities Engineering Service Center (NFESC) was invited to participate in this development, because of NFESC's expertise and the Navy's extensive experience with a wide variety of waterfront facilities.

1.1 PURPOSE

The purpose of this report is to document and make recommendations on mooring design and inspection criteria. The Navy has recently completed a draft of "Mooring Design" MIL-HDBK-1026/4 (Seelig ed. of 1998) that addresses many of the items of interest. In this report the Navy standards are compared with various commercial codes. Examples are shown that compare the codes and recommendations are made.

2.0 CRITERIA

Criteria are provided for design and inspection of mooring facilities. The major emphasis of the criteria are for ‘fixed’ mooring facilities (i.e. ships at piers and wharves).

2.1 U.S. NAVY CRITERIA

The U.S. Navy owns ships and mooring facilities throughout the world, included facilities for tankers and similar ships. In the past, different criteria documents were provided for ship mooring systems and facilities mooring systems. However, in 1997-1998 all the criteria were updated and combined into MIL-HDBK-1026/4 “Mooring Design” (Seelig, ed. 1998). This handbook is intended for all classes of ships, including tankers. Appendix A includes Sections 3 and 4 of the handbook, which provides mooring design and inspection criteria, as well as methods for calculating wind and current forces/moments.

A key development provided in MIL-HDBK-1026/4 is the concept of *Mooring Service Type*. The U.S. Navy provides four types of mooring service, as shown in Table 6 (page 2-5) of Appendix A. These types of mooring are ranked from lowest to highest risk of a storm striking with a ship in the mooring. Design criteria are specified with each *Mooring Service Type* to minimize the risk of an accident.

Mooring Service Types I&II take care of cases with a ship moored one month or less, which is primarily the case at fuel facilities. Design criteria for these types of service are given in Table 7 (page 2-7) of Appendix A, which are shown in Table 2.1.

The wind criteria for design of this service type range from a 30-second wind speed of 33 knots to a wind with a return interval of R=25 years, up to 75 mph. MIL-HDBK-1026/4 uses ASCE 7-97 to specify design wind speeds. However, ASCE 7-95 also allows actual wind statistics to be used for site design, if adequate measured wind data is available for a site.

Water level, current and wave design criteria are shown in Table 2.1.

Locations of U.S. Navy design criteria from Section 3 of MIL-HDBK-1026/4 are given in Appendix A and locations of key information are given in Table 2.2.

If ships of similar size are moored alongside one another or nearby, then methods in Appendix A of MIL-HDBK-1026/4 can be used to determine environmental forces and moments on the ships.

Table 2.1 FACILITY DESIGN CRITERIA FOR *MOORING SERVICE TYPES I&II*

MOORING SERVICE TYPE	WIND*	CURRENT**	WATER LEVEL	WAVES
TYPE I	Less than 34 knots	2 knots or less	mean lower low to mean higher high	P=1 or R=1 yr
TYPE II	P=0.04 (min.) R=25 yr (min.) V_w=64 knots (max.)	P=0.04 R=25 yr	extreme lower low to mean higher high	P=1 or R=1 yr

*Use exposure D (American Society of Civil Engineers (ASCE) 7-95, Minimum Design Loads for Buildings and Other Structures; flat, unobstructed area exposed to wind flowing over open water for a distance of at least 1 mile or 1.61 km) for determining design wind speeds. Note that min. = minimum return interval or probability of exceedence used for design; max. = maximum wind speed used for design.

**To define the design water depth, use T/d=0.9 for flat keeled ships; for ships with non-flat hulls, that have sonar domes or other projections, take the ship draft, T, as the mean depth of the keel and determine the water depth, d, by adding 0.61 meter (2 feet) to the maximum navigation draft of the ship.

Table 2.2 KEY *MOORING SERVICE TYPE I* CRITERIA

CRITERIA	*SOURCE**	*PAGE**
	Section 3	
Definitions of *Mooring Service Types*	Table 6	2-5
Design criteria	Table 7	2-7
Minimum quasi-static factors of safety	Table 9	2-10
Ship motion criteria	Table 10	2-11 to14
Quasi-static approach	Table 11	2-15
Conditions requiring special analyses	Table 12	2-18
Design considerations - facilities	Table 14	2-25
Mooring operational design considerations	Table 18	2-42
Inspections guidelines	Table 19	2-43 to 44
Design recommendations	Table 20	2-46 to 47
Quasi-static forces and moments on ships	***Section 4***	2-48

*See Appendix A

2.2 OCIMF CRITERIA

Oil Companies International Marine Forum (OCIMF) has developed various criteria specifically intended for tankers. These include:

Oil Companies International Marine Forum (OCIMF), Mooring Equipment Guidelines, 1nd Edition, 1992.

Oil Companies International Marine Forum (OCIMF), Recommendations for Equipment Employed in the Mooring of Ships at Single Point Moorings, 3nd Edition, 1993.

Oil Companies International Marine Forum (OCIMF), Prediction of Wind and Current Loads on VLCCs, 2nd Edition, 1994.

Oil Companies International Marine Forum (OCIMF), Single Point Mooring Maintenance and Operations Guide, 2nd Edition, 1995.

Note that both the Navy and OCIMF have both recently changed their sign convention and reference coordinate systems to conform to the standard right-hand-rule and both use the same system. Both the Navy and OCIMF use the wind speed at 10 m as a reference. The Navy specifies a wind gust with a duration of 30-seconds, while OCIMF does not address wind gusts, but states “While vessels may respond to wind gusts of limited duration, the analysis of this subject is beyond the scope of this report.”

2.3 OTHER CRITERIA

Various other sources address specific criteria. Some of these references include:

American Petroleum Institute, “Recommended Practice for Planning, Designing, and Constructing Tension Leg Platforms”, API RP 2T, April 1, 1987.

American Petroleum Institute, “Analysis of Spread Mooring Systems for Floating Drilling Units”, ANSI/API RP 2P-87, Approved July 12, 1993.

American Petroleum Institute, “Recommended Practice for Design, Analysis, and Maintenance of Moorings for Floating Production Systems”, ANSI/API RP 2FP1-93, Approved April 13, 1994.

American Petroleum Institute, “Recommended Practice for Design and Analysis of Stationkeeping Systems for Floating Structures”, API RP 2SK, 2nd Ed., Mar. 1, 1997.

Permanent International Association of Navigation Congresses, “Report of the International Commission for Improving the Design of Fender Systems”, Supplement to Bulletin No. 45, 1984.

Permanent International Association of Navigation Congresses, “Criteria for Movements of Moored Ships in Harbours; A Practical Guide”, Report of Working Group No. 24 of the Permanent Technical Committee II, Supplement to Bulletin No. 88, 1995.

These and similar references address various aspects of mooring. Some of the references are oriented towards offshore facilities, while others address specific aspects of a facility. In MIL-HDBK-1026/4, many references were reviewed and key items of interest were then considered and incorporated into the handbook.

3.0 COMPARISONS OF CRITERIA

3.1 GENERAL

MIL-HDBK-1026/4 (draft of 1998) was organized to be a comprehensive manual that addresses mooring design and inspection. Extensive U.S. Navy experience, together with a number of other references, were considered in preparing the manual. It was found that many of the other references did not specifically address waterfront 'fixed' mooring facilities (i.e. piers and wharfs) as extensively as the Navy methods. Therefore, portions of these other references were considered and then incorporated into the Navy manual, if appropriate.

The approach in MIL-HDBK-1026/4 was to use quasi-static methods and indicate conditions that may require further dynamic analysis. The handbook was designed to include almost any class of vessels, including tankers. A discussion of specific items is provided below.

Risk

A wind return interval of R=25 years was selected for *Mooring Service Type II* as providing reasonable risk. Facilities offering this type of service are often occupied. However, these vessels should be ready to go and leave the facility if extreme weather is predicted.

Factors of Safety

Factors of safety were selected so that mooring lines are the weak link, because lines are most easily tested and replaced when necessary. Facilities have slightly higher factors of safety, because they are designed to last longer and are more difficult to inspect and replace. Also, a facility may have a visit by some ship larger than originally envisioned when the facility was designed.

The design approach selects an extreme event. Calculations are performed assuming quasi-static conditions. Factors of safety are then selected to provide low risk at reasonable cost. They help account for typical factors, such as:

mild dynamics of the system

material wear

variability in use

uncertainty in calculations

unknown factors

3.2 COMPARISONS OF FORCES

MIL-HDBK-1026/4 and OCIMF (1994) provide methods for estimating forces and moments on ships. Some of the key items concerning these methods are:

MIL-HDBK-1026/4 method:

For any vessel.

Uses 30-second duration wind speed.

Broadside wind drag coefficient considers elevation of hull and superstructure to come up with an effective drag coefficient.

Broadside current drag coefficient is a function of the hull shape and ratio of draft to water depth.

Longitudinal current drag is computed for the form, friction and propeller.

General shape functions are provided for wind and current forces/moments.

OCIMF method:

For tankers only.

Wind gust duration not specified.

Separate broadside wind coefficients given for loaded and light vessels.

Longitudinal current coefficient given.

Shape functions are given graphically for selected parameters. These are sometimes rather complex.

Selected comparison are shown to compare MIL-HDBK-1026/4 and OCIMF methods. Tankers are of special interest to the California State Lands Commission, so a 200,000 DWT tanker with principle dimensions given in Table 3.1 is used to illustrate the computed forces.

Table 3.1 TYPICAL 200,000 DWT TANKER PARAMETES (after Wichers)

PARAMETER	*LOADED*	*LIGHT (BALLASTED)*
Length between perp.	310 m	310 m
Draft	18.9 m	7.56 m
Width	47.17 m	47.17 m
Disp. Volume	234,994 m^2	88,956 m^2
End-on Wind Area	1362.4 m^2	1897.3 m^2
Side Wind Area Hull	3461.4 m^2	7095.9 m^2
Side Wind Area Super.	922 m^2	922 m^2
Height of Hull	10.8 m	22.14 m
Height of Superstructure	32.2 m	43.64

Various force coefficients and forces are compared here to illustrate MIL-HDBK-1026/4 and OCIMF methods. In this report a drag coefficient is defined as a force divided by (0.5*density*exposed area*velocity squared).

Figure 3.1 and 3.2 show that longitudinal wind drag coefficients for 0-degrees (OCIMF Figure 2) and broadside wind drag coefficients for 90-degrees (OCIMF Figure 3) are similar to those computed using MIL-HDBK-1026/4.

A direct comparison of longitudinal forces for a 3-knot current shows that OCIMF and MIL-HDBK-1026 give similar results for a loaded tanker (Figure 3.3). The MIL-HDBK-1026/4 method predicts that a significant portion of the drag is due to the skin friction and propeller drag, so that a lightly loaded tanker has somewhat less current drag forces. OCIMF gives an unexpectedly smaller value for a lightly loaded tanker.

A comparison of broadside current drag coefficients shows the MIL-HDBK-1026/4 prediction fit the OCIMF (Figure 10) data very well, as shown in Figure 3.4.

The MIL-HDBK-1026/4 recommended shapes of forces and moments as a function of direction that are shown for wind in Figure 3.5 and for current in Figure 3.6. The OCIMF shape factors are much more complex and vary as a function of a number of parameters.

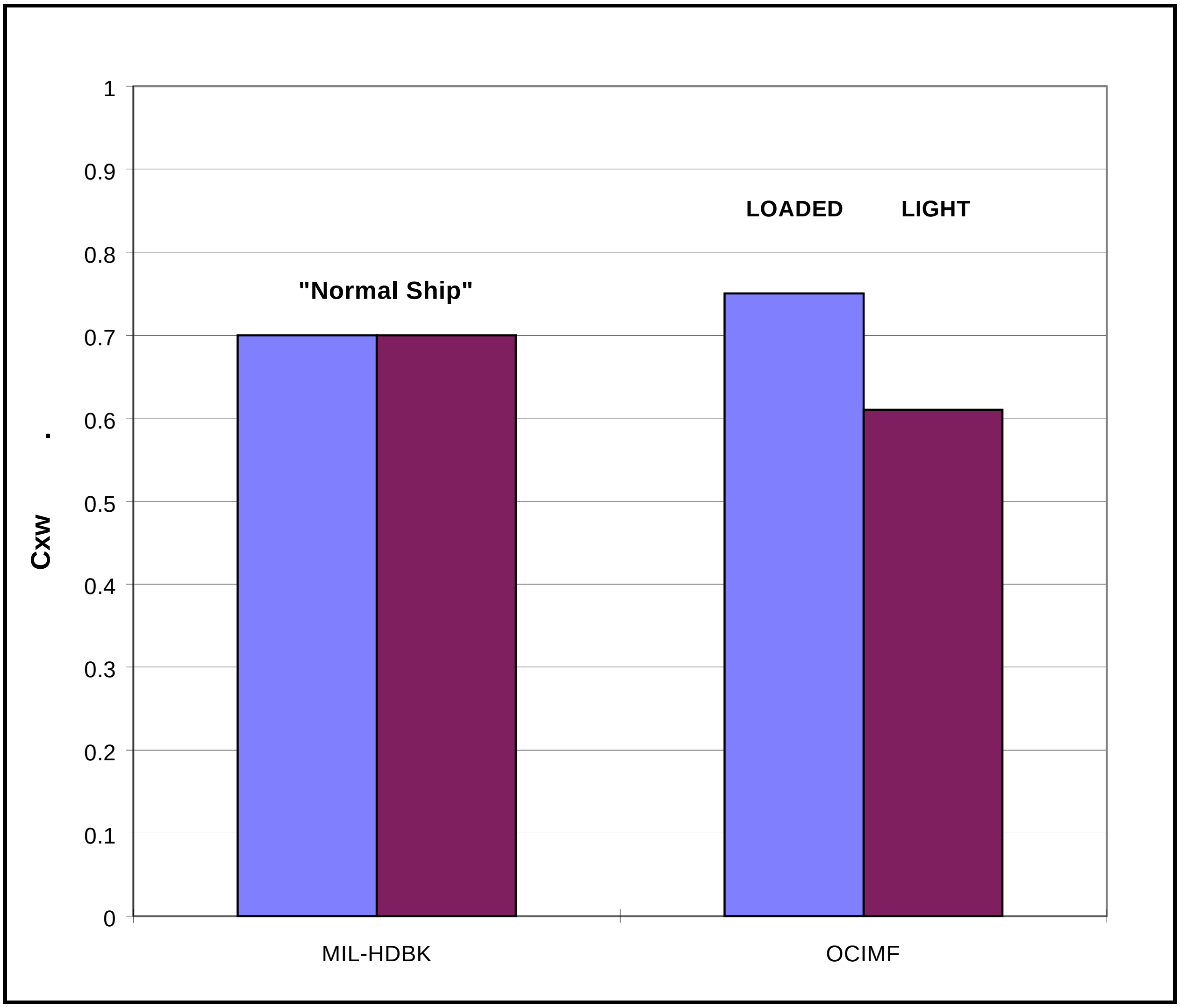

Figure 3.1 WIND DRAG COEFFICIENTS FOR 0-DEGREES

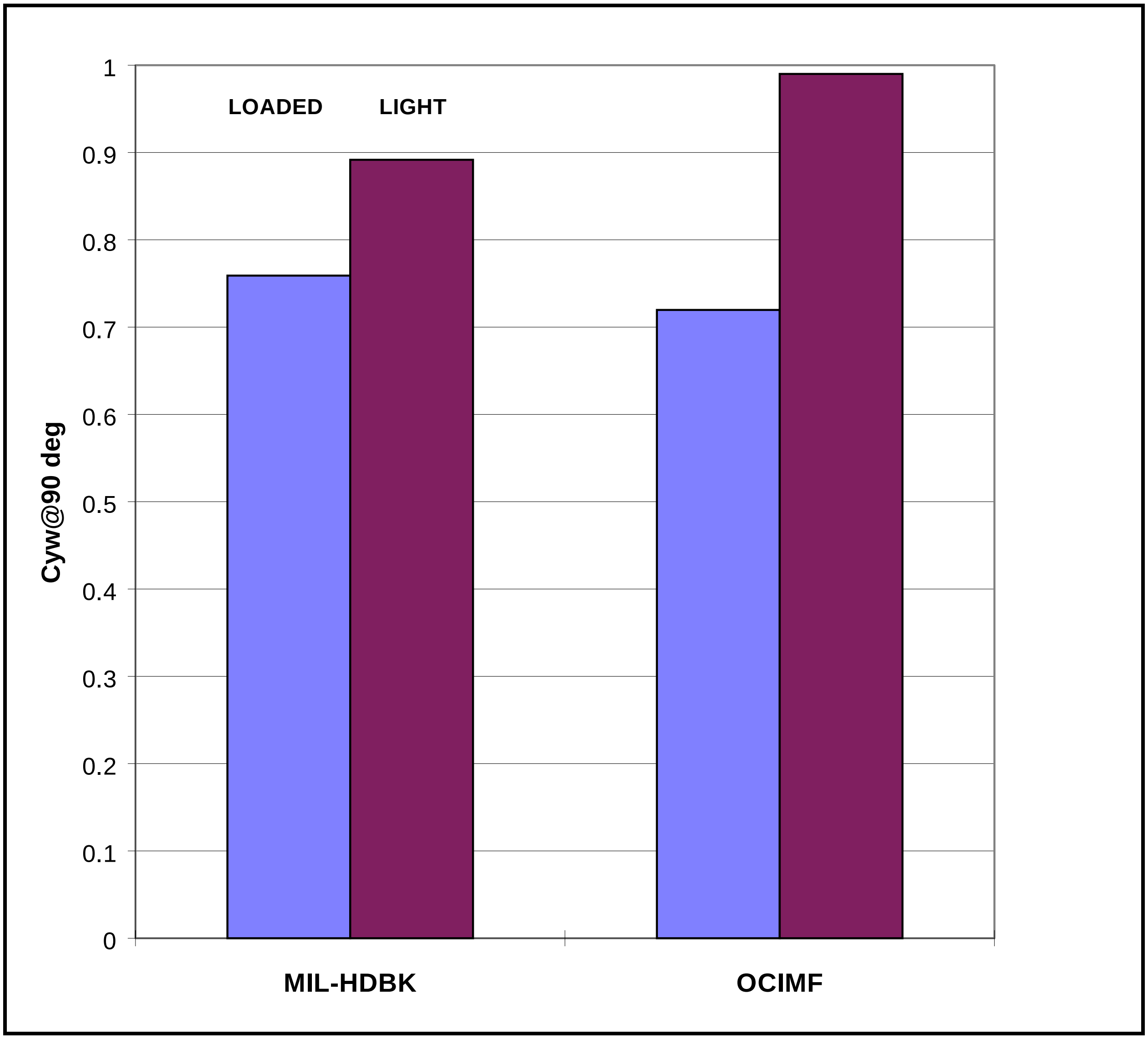

Figure 3.2 BROADSIDE WIND DRAG COEFFICIENTS

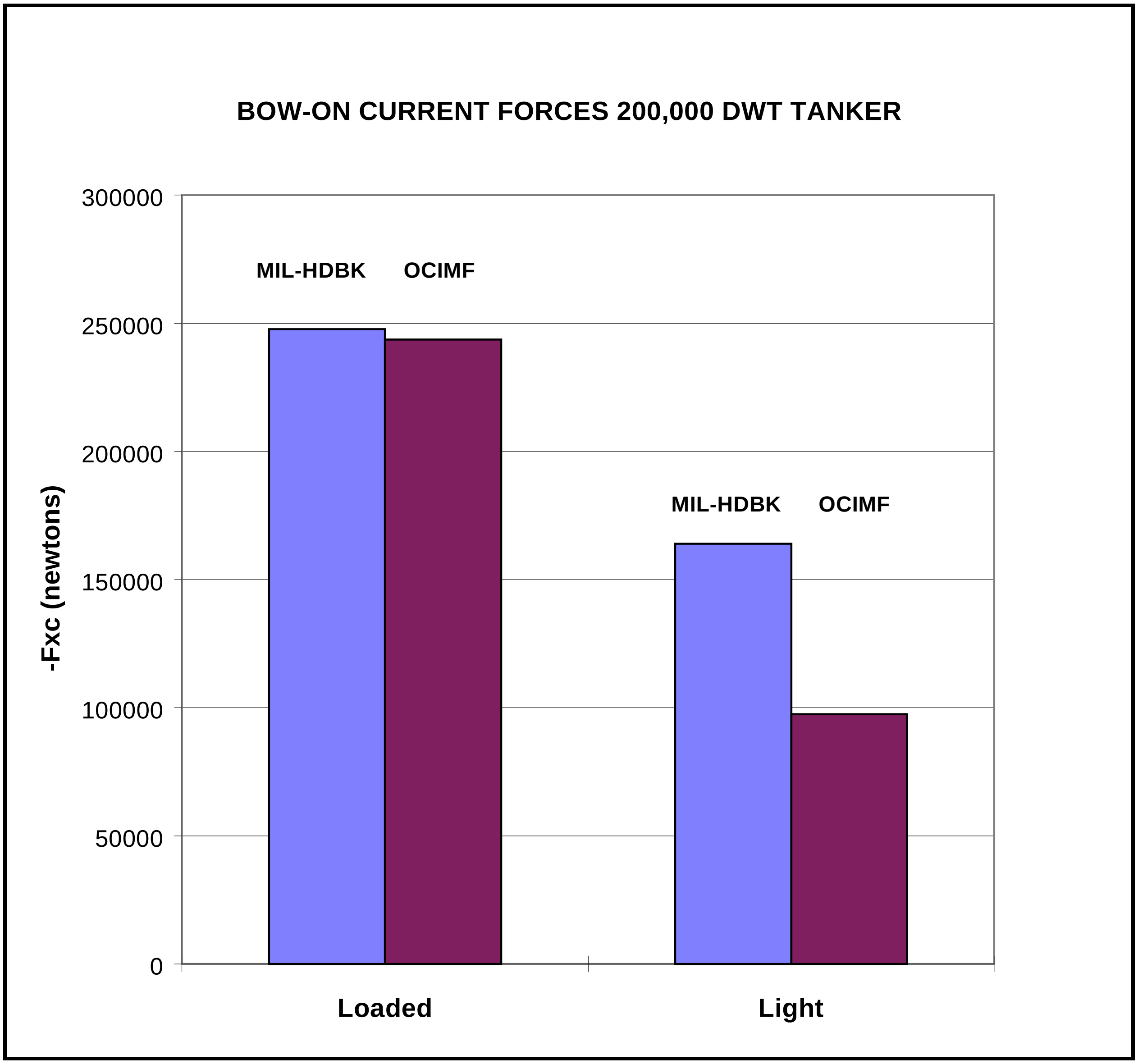

Figure 3.3 END-ON CURRENT FORCES FOR A 3-KNOT CURRENT

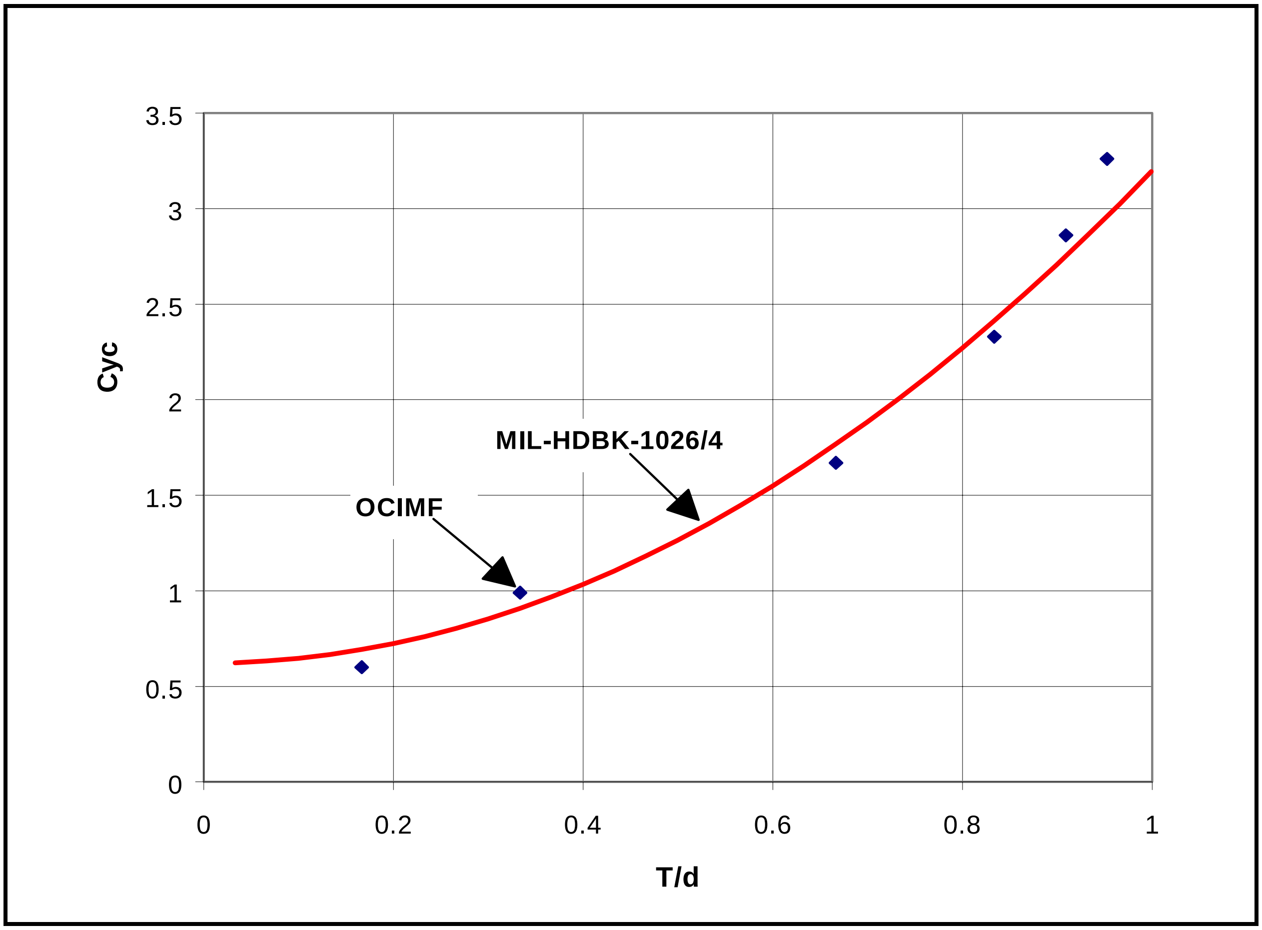

Figure 3.4 BROADSIDE CURRENT DRAG COEFFICIENT PREDICTED FOR A 200,000 DWT TANKER

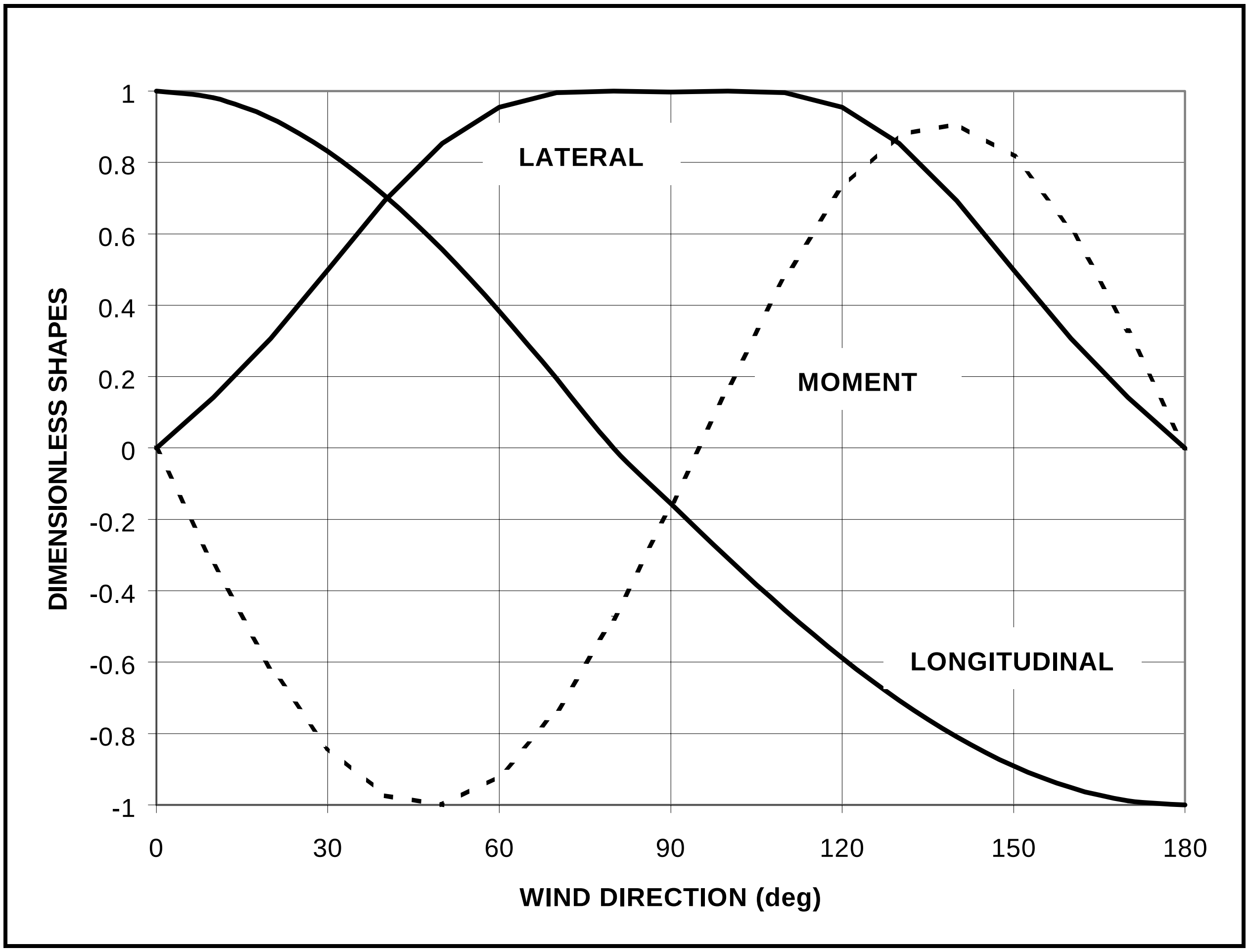

Figure 3.5 WIND FORCE/MOMENT SHAPES

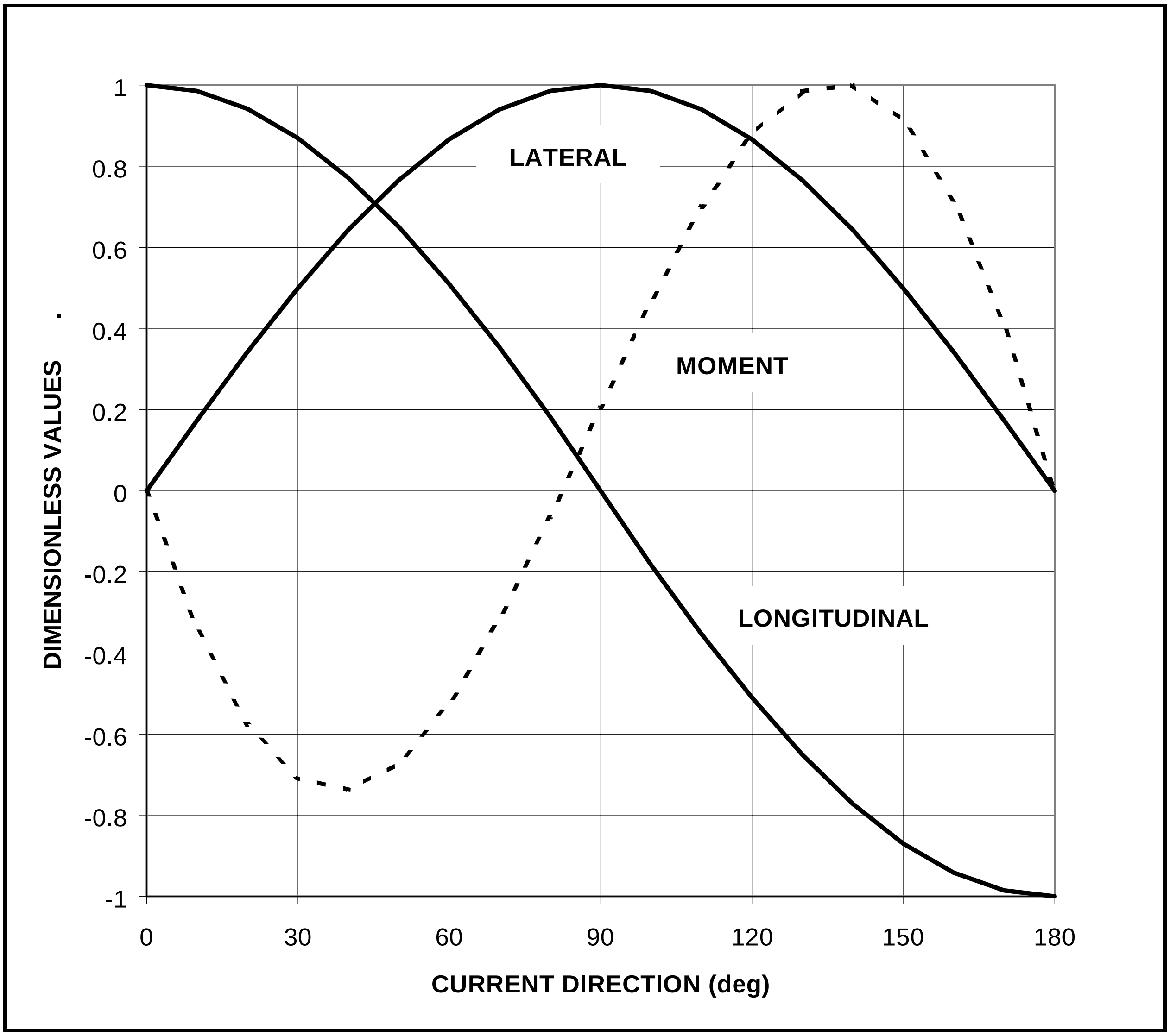

Figure 3.6 CURRENTFORCE/MOMENT SHAPES

4.0 DESIGN WIND SPEEDS

Environmental design criteria includes winds, tides, current and waves (if necessary). Water depths must also be known. Tides and currents can often be determined from NOAA records and the U.S. Army Corps of Engineers commonly has dredging records. Winds are then of special interest. *Mooring Service Type I* specifies a 30-second duration wind speed with a return interval of R=25 years (probability of P=0.04) with a minimum wind speed of 33 knots.

ASCE 7-95 gives a 3-second R=50 year design wind speed of 85 mph for all of California. This can be converted to a 30-second R=25 year design wind speed with Exposure D (wind flowing over open water for a distance of at least 1 mile or 1.61 km) to:

$$85 \text{ mph} * 0.87 * 1.086 * 0.93 = 74.68 \text{ mph}$$

More localized values of R=25 year 30-second duration wind speed values can be determined from taking R=50 fastest mile wind speeds from NUREG/CR-4801 and converting them using methods in ASCE 7-95 for R=25 years, 30-second duration and Exposure D. Table 4-1 gives these design wind speeds. Figures 4-1 and 4-2 show these design wind speeds in graphical form.

Table 4-1. R=25 YEAR 30-SECOND EXPOSURE D WIND SPEEDS

Location	(mph)
Alameda	61.6
Bakersfield	59.6
Bishop	70.4
Blue Canyon	91.3
Chula Vista/Brown	42.0
Coronodo/North Island	58.6
Edwards	64.5
El Centro	75.2
El Toro	75.2
Fairfield/Travis	65.5
Fresno	50.5
Imperial Beach/Ream	58.6
Inyokern/China Lake	67.5
Lemoore	53.6
Long Beach	65.5
Los Alamitos	51.6
Los Angeles Airport	53.6
Los Angeles City	43.1
Marysville/Bewale	64.5
Merced/Castle	54.6
Monterey	64.5
Mt. Tamalpias	138.8
Mt. Tamalpias	135.1
Oakland	62.6
Oxnard	55.6
Point Mugu	67.5
Point Reyes	112.8
Riverside/March	51.6
Sacramento	69.4
Scramento/Mather	64.5
Scramento/McClellan	72.3
San Bernadrino/Norton	68.4
San Clemente Island	54.6
San Diego	64.5
San Diego/Miramar	51.6
San Francisco City	54.6
San Francisco Airport	72.3
San Jose	52.6
San Nicholas Island	56.6
San Rafael/Hamilton	68.4
Sandberg	98.8
Santa Ana	65.5
Stockton	68.4
Sunnyvale/Moffett	53.6
Vandenberg	55.6
Victorville/George	68.4
Yuma, Arizona	63.6

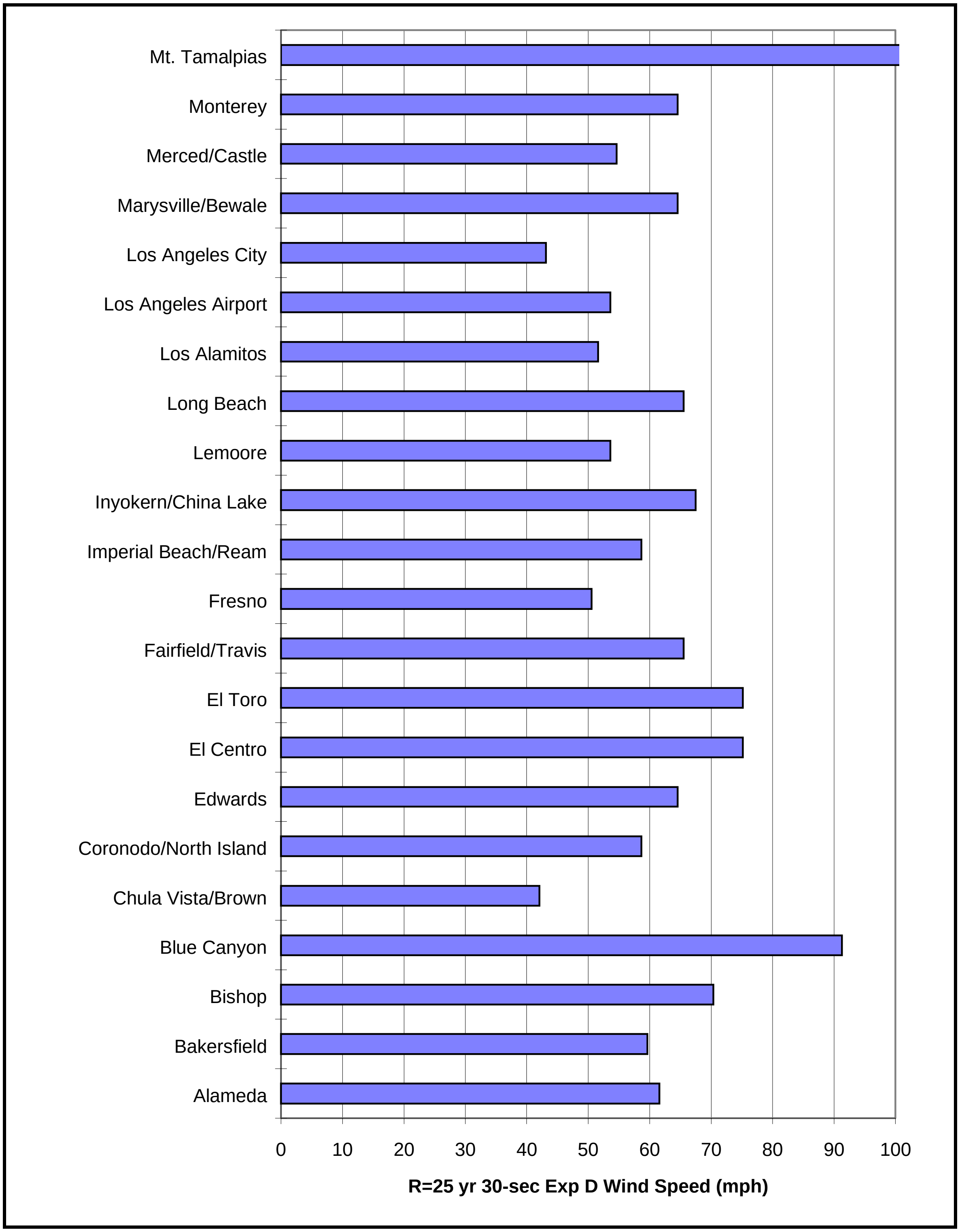

Figure 4.1 R=25 YR 30-SEC EXP D DESIGN WIND SPEEDS

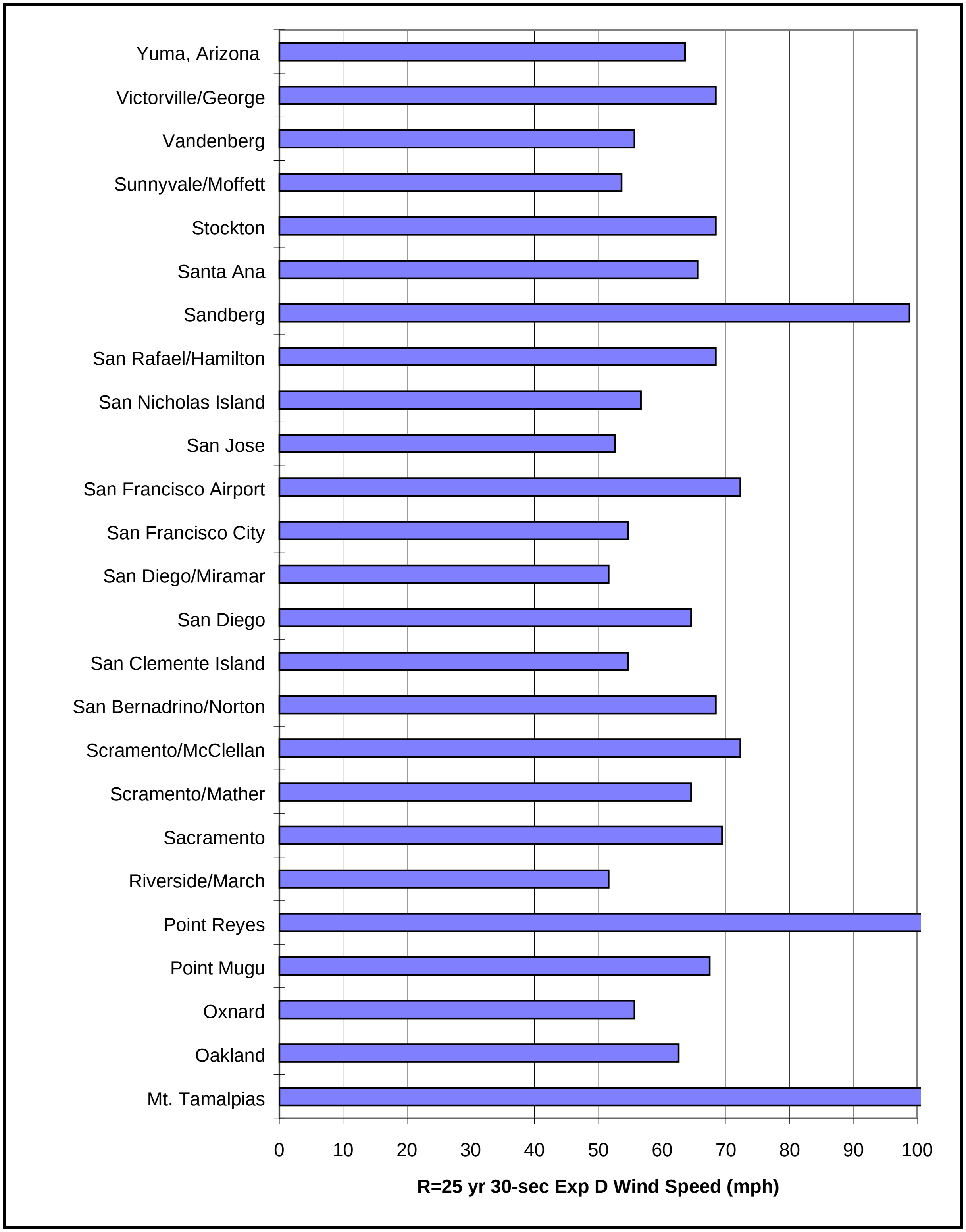

Figure 4.2 R=25 YR 30-SEC EXP D DESIGN WIND SPEEDS CONT.

5.0 SUMMARY AND RECOMMENDATIONS

The U.S. Navy is extremely interested in safely mooring ships. Therefore MIL-HDBK-1026/4 (draft of 1998) was recently funded. It is designed to be a comprehensive guide for design and inspection of mooring facilities. Many references were consulted in developing this manual. This manual was designed for all classes of ships, including tankers. The State of California may want to consider adopting or incorporating this manual into their criteria.

Mooring analyses tools, a U.S. Navy ships' database, a climate database and a facilities database are being designed to work with MIL-HDBK-1026/4. This will allow the user to quickly and easily perform computations. The State of California may wish to participate in development of these items.

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APPENDIX A. OUTLINE OF MIL-HDBK-1026/4 'MOORING DESIGN'

APPENDIXES

APPENDIX B. SECTIONS 3 AND 4 FROM MIL-HDBK-1026/4

These chapters from the draft military handbook describe design criteria and wind and current forces/moments.

Section 3: BASIC DESIGN PROCEDURE

3.1 Design Approach. Begin the design with specified parameters and use engineering principles to complete the design. Types of parameters associated with mooring projects are summarized in Table 3. The basic approach to performing mooring design with the ship known is given in Table 4.

Table 3
Parameters in a Mooring Project

PARAMETER	EXAMPLES
1. Operational Parameters	Required ship position, amount of motion allowed
2. Ship Configuration	Basic ship parameters, such as length, width, draft, displacement, wind areas, mooring fitting locations, wind/current force, and moment coefficients
3. Facility Configuration	Facility location, water depth, dimensions, locations/type/capacity of mooring fittings/fenders, facility condition, facility overall capacity
4. Environmental Parameters	Wind speed, current speed and direction, water levels, wave conditions and possibility of ice
5. Mooring Configuration	Number/size/type/location of tension members, fenders, camels, etc.
6. Material Properties	Stretch/strain characteristics of the mooring tension and compression members

Table 4

Basic Mooring Design Approach with Known Facility for a Specific Site and a Specific Ship

STEP	NOTES
Define customer(s) requirements	Define the ship(s) to be moored, the type of service required, the maximum allowable ship motions, and situations under which the ship will leave.
Determine planning requirements	Define the impact/interaction with other facilities and operations, evaluate explosive arcs, determine permit requirements, establish how the mooring is to be used, review the budget and schedule.
Define site and environmental parameters	Determine the water depth(s), engineering soil parameters, design winds, design currents, design waves, design water levels, and evaluate access.
Ship characteristics	Find the engineering characteristics of the ship(s) including sail areas, drafts, displacements, ship mooring fittings, allowable hull pressures, and other parameters.
Ship forces/moments	Determine the forces, moments, and other key behaviors of the ship(s).
Evaluate mooring alternatives	Evaluate the alternatives in terms of safety, risk, cost, constructability, availability of hardware, impact on the site, watch circle, compatibility, maintenance, inspectability, and other important aspects.
Design Calculations	Perform static and/or dynamic analyses (if required) for mooring performance, anchor design, fender design, etc

Table 4
Basic Mooring Design Approach with Known Facility for a Specific Site and a Specific Ship (Continued)

STEP	NOTE
Plans/Specs	Prepare plans, specifications, and cost estimates.
Permits	Prepare any required environmental studies and obtain required permits.
Installation planning	Prepare instructions for installation, including safety and environmental protection plans.
Installation monitoring	Perform engineering monitoring of the installation process.
Testing	Perform on-site tests of the installed system, as required, to ensure the mooring works as designed. Full-scale anchor proof tests are recommended.
Documentation	Document the design and as-built conditions with drawings and reports.
Instructions	Provide diagrams and instructions to show the customer how to use and inspect the mooring.
Inspection	Perform periodic inspection/testing of the mooring to assure it continues to meet the customer(s) requirements.
Maintenance	Perform maintenance as required and document on as-built drawings.

3.2 General Design Criteria. General design issues shown in Table 5 should be addressed during design to help ensure projects meet customers' needs.

Table 5

Design Issues

CRITERIA	NOTES
Vessel operating conditions	Under what conditions will the vessel(s) exit? What are the operating mission requirements for the ship? What is the maximum allowable hull pressure?
Allowable motions	How much ship motion in the six degrees-of-freedom will be allowable for the moored ship? This is related to brow positions and use, utilities, ship loading and unloading operations, and other requirements. Note that most ships have a very high buoyancy force and moorings should be designed to allow for water level changes at a site.
User skills	Is the user trained and experienced in using the proposed system? What is the risk that the mooring would be improperly used? Can a design be formulated for easy and reliable use?
Flexibility	How flexible is the design? Can it provide for new mission requirements not yet envisioned? Can it be used with existing facilities/ships?
Constructability	Does the design specify readily available commercial products and is it able to be installed and/or constructed using standard techniques, tolerances, etc.?
Cost	Are initial and life cycle costs minimized?
Inspection	Can the mooring system be readily inspected to ensure continued good working condition?
Maintenance	Can the system be maintained in a cost-effective manner?
Special requirements	What special requirements does the customer have? Are there any portions of the ship that cannot come in contact with mooring elements (e.g., submarine hulls)?

3.2.1 Mooring Service Types. There are several types of standard services that moorings provide for DOD vessels in harbors. Therefore, the facilities and ship's mooring hardware should accommodate the types of services shown in Table 6.

Table 6
Mooring Service Types

MOORING SERVICE TYPE	DESCRIPTION
TYPE I	This category covers moorings that are used for **up to 1 month** by a vessel that **will leave** prior to an approaching tropical hurricane, typhoon, or flood. Moorings include ammunition facilities, fueling facilities, deperming facilities, and ports of call. Use of these moorings is normally selected concomitant with forecasted weather.
TYPE II	This category covers moorings that are used for **1 month or more** by a vessel that **will leave** prior to an approaching tropical hurricane, typhoon, or flood. Moorings include general purpose berthing facilities.
TYPE III	This category covers moorings that are used for **up to 2 years** by a vessel that **will not leave** prior to an approaching tropical hurricane or typhoon. Moorings include fitting-out, repair, drydocking, and overhaul berthing facilities. Ships experience this service approximately every 5 years. Facilities providing this service are nearly always occupied.
TYPE IV	This category covers moorings that are used for **2 years or more** by a vessel that **will not leave** in case of a hurricane, typhoon, or flood. Moorings include inactive, drydock, ship museum, and training berthing facilities.

3.2.2 Facility Design Criteria for Mooring Service Types. Mooring facilities should be designed using the site specific criteria given in Table 7. Table 7 gives design criteria in terms of environmental design return intervals, R, and in terms of probability of exceedence, P, for 1 year of service life, N=1.

3.2.3 Ship Hardware Design Criteria for Mooring Service Types. Ship mooring hardware needs to be designed to accommodate various modes of ship operation. During Type II operation, a ship may be moored in relatively high broadside current and get caught by a sudden storm, such as a thunderstorm. Type III mooring during repair may provide the greatest potential of risk, because the ship is moored for a significant time and cannot get underway. During Type IV mooring, the ship should be aligned with the current, extra padeyes can be welded to the ship hull for mooring, etc., so special provisions can be made for long-term storage. There are several U.S. shipyards where DOD ships can undergo major repairs. The area near Norfolk/Portsmouth, Virginia has the most extreme design criteria, so use conditions derived from that site for the ship's hardware design. Bremerton, Washington, and Pearl Harbor, Hawaii have major U.S. Navy repair shipyards with lower design winds and currents at those sites. Ship mooring hardware environmental design criteria are given in Table 8.

3.2.4 Strength. Moorings should be designed and constructed to safely resist the nominal loads in load combinations defined herein without exceeding the appropriate allowable stresses for the mooring components. Normal wear of materials and inspection methods and frequency need to be considered. Due to the probable chance of simultaneous maximum occurrences of variable loads, no reduction factors should be used.

3.2.5 Serviceability. Moorings should be designed to have adequate stiffness to limit deflections, vibration, or any other deformations that adversely affect the intended use and performance of the mooring. At the same time moorings need to be flexible enough to provide for load sharing and allow for events, such as tidal changes.

Table 7
Facility Design Criteria for Mooring Service Types

MOORING SERVICE TYPE	WIND*	CURRENT**	WATER LEVEL	WAVES
TYPE I	V_w=33 knts(min.) P=0.04 R=25 yr V_w=75 mph (max.)	average max. current	mean lower low to mean higher high	P=1 or R=1 yr
TYPE II	P=0.02 (min.) R=50 yr (min.) V_w=75 mph (max.)	P=0.02 R=50 yr	extreme lower low to mean higher high	P=1 or R=1 yr
TYPE III	P=0.02 or R=50 yr	P=0.02 or R=50 yr	extreme lower low to high	P=0.02 or R=50 yr
TYPE IV	P=0.01 or R=100 yr	P=0.01 or R=100 yr	extreme water levels	P=0.01 or R=100 yr

*Use exposure D (American Society of Civil Engineers (ASCE) 7-95, Minimum Design Loads for Buildings and Other Structures; flat, unobstructed area exposed to wind flowing over open water for a distance of at least 1 mile or 1.61 km) for determining design wind speeds. Note that min. = minimum return interval or probability of exceedence used for design; min. = minimum wind speed; max. = maximum wind speed used for design.

**To define the design water depth, use T/d=0.9 for flat keeled ships; for ships with non-flat hulls, that have sonar domes or other projections, take the ship draft, T, as the mean depth of the keel and determine the water depth, d, by adding 0.61 meter (2 feet) to the maximum navigation draft of the ship.

Table 8
Ship Mooring Hardware Design Criteria

a. Ship Anchor Systems*

MAXIMUM WATER DEPTH	MINIMUM WIND SPEED	MINIMUM CURRENT SPEED	CHAIN FACTOR OF SAFETY	ANCHOR HOLDING FACTOR OF SAFETY
240 ft 73 m	70 knots 36.0 m/s	4 knots 2.06 m/s	4.0	1.0

b. Submarine Anchor Systems*

MAXIMUM WATER DEPTH	MINIMUM WIND SPEED	MINIMUM CURRENT SPEED	CHAIN FACTOR OF SAFETY	ANCHOR HOLDING FACTOR OF SAFETY
90 ft 27.4 m	70 knots 36.0 m/s	4 knots 2.06 m/s	4.0	1.0

c. Ship Mooring Systems**

CONDITION	MINIMUM WIND SPEED	MINIMUM CURRENT SPEED	MOORING LINE FACTOR OF SAFETY
Normal weather condition	25 knots 12.9 m/s	1 knot 0.51 m/s	9.0
Heavy weather condition	50 knots 25.7 m/s	3 knots 1.54 m/s	3.0

*Quasi-static design assuming wind and current are co-linear for ship and submarine anchor systems (after NAVSEA DDS-581).
**Quasi-static design assuming current is broadside and wind can approach from any direction (after NAVSEA DDS-582-1).

3.2.6 General Mooring Integrity. For multiple-member moorings, such as for a ship secured to a pier by a number of lines, the mooring system strongly relies on load sharing among several members. If one member is lost, the ship should remained moored. Therefore, a multiple member mooring design should be designed to ensure that remaining members maintain a factor of safety at least 75 percent of the intact mooring factors of safety shown in Table 9 with any one member missing.

3.2.7 Quasi-Static Safety Factors. Table 9 gives recommended minimum factors of safety for "quasi-static" design based on material reliability.

3.2.8 Allowable Ship Motions. Table 10 gives recommended operational ship motion criteria for moored vessels. Table 10(a) gives maximum wave conditions for manned and moored small craft (Permanent International Association of Navigation Congresses (PIANC), Criteria for Movements of Moored Ships in Harbors; A Practical Guide, 1995). These criteria are based on comfort of personnel on board a small boat, and are given as a function of boat length and locally generated.

Table 10(b) gives recommended motion criteria for safe working conditions for various types of vessels (PIANC, 1995).

Table 10(c) gives recommended velocity criteria and Table 10(d) and (e) give special criteria.

Table 9

Minimum Quasi-Static Factors of Safety

COMPONENT	MINIMUM FACTOR OF SAFETY	NOTES
Stockless anchor	1.5	For ultimate anchoring system holding capacity*
High efficiency drag anchors	2.0	For ultimate anchoring system holding capacity*
Fixed anchors (piles and plates)	3.0	For ultimate anchoring system holding capacity*
Deadweight anchors	-	Use only in special cases (see Naval Civil Engineering Laboratory (NCEL) Handbook for Marine Geotechnical Engineering, 1985)
Chain	3.0 4.0	For relatively straight lengths. For chain around bends. These factors of safety are for the new chain break strength.
Wire rope	3.0	For the new wire rope break strength.
Synthetic line**	3.0	For new line break strength.
Ship bitts	***	For ultimate strength.
Pier bollards	***	For ultimate strength.

*It is recommended that anchors be pull tested.
**Reduce the effective strength of wet nylon line by 15 percent.

*** For mooring fittings take 3 parts of the largest size of line used on the fitting; apply a load of: 3.0*(minimum line break strength)*1.3 to determine actual stresses, $_{act.}$; design fittings so ($_{act.}$/ $_{allow.}$)<1.0, where $_{allow.}$is the allowable stress from AISC and other applicable codes.

Table 10

Recommended Practical Motion Criteria for Moored Vessels

(a) Safe Wave Height Limits for Moored Manned Small Craft
(after PIANC, 1995)

	Beam/Quartering Seas		Head Seas	
Ship Length (m)	Wave Period (sec)	Maximum Sign Wave Height, H_S (m)	Wave Period (sec)	Maximum Sign Wave Height, H_S (m)
4 to 10	<2.0	0.20	<2.5	0.20
“	2.0-4.0	0.10	2.5-4.0	0.15
“	>4.0	0.15	>4.0	0.20
10-16	<3.0	0.25	<3.5	0.30
“	3.0-5.0	0.15	3.5-5.5	0.20
“	>5.0	0.20	>5.5	0.30
20	<4.0	0.30	<4.5	0.30
“	4.0-6.0	0.15	4.5-7.0	0.25
“	>6.0	0.25	>7.0	0.30

Table 10
Recommended Practical Motion Criteria for
Moored Vessels (Continued)

(b) Recommended Motion Criteria for Safe Working Conditions[1]
(after PIANC, 1995)

Ship Type	Cargo Handling Equipment	Surge (m)	Sway (m)	Heave (m)	Yaw (°)	Pitch (°)	Roll (°)
Fishing vessels 10-3000 GRT[2]	Elevator crane	0.15	0.15	-	-	-	-
	Lift-on/off	1.0	1.0	0.4	3	3	3
	Suction pump	2.0	1.0	-	-	-	-
Freighters & coasters <10000 DWT[3]	Ship's gear	1.0	1.2	0.6	1	1	2
	Quarry cranes	1.0	1.2	0.8	2	1	3
Ferries, Roll-On/ Roll-Off (RO/RO)	Side ramp[4]	0.6	0.6	0.6	1	1	2
	Dew/storm ramp	0.8	0.6	0.8	1	1	4
	Linkspan	0.4	0.6	0.8	3	2	4
	Rail ramp	0.1	0.1	0.4	-	1	1
General cargo 5000-10000 DWT	-	2.0	1.5	1.0	3	2	5
Container vessels	100% efficient	1.0	0.6	0.8	1	1	3
	50% efficient	2.0	1.2	1.2	1.5	2	6
Bulk carriers 30000-150000 DWT	Cranes	2.0	1.0	1.0	2	2	6
	Elevator/ bucket-wheel	1.0	0.5	1.0	2	2	2
	Conveyor belt	5.0	2.5	-	3	-	-
Oil tankers	Loading arms	3.0[5]	3.0	-	-	-	-
Gas tankers	Loading arms	2.0	2.0	-	2	2	2

Notes for Table 10(b):
[1]Motions refer to peak-to-peak values (except for sway, which is zero-to-peak)
[2]GRT = Gross Registered Tons expressed as internal volume of ship in units of 100 ft^3 (2.83 m^3)

[3]DWT = Dead Weight Tons, which is the total weight of the vessel and cargo expressed in long tons (1016 kg) or metric tons (1000 kg)

[4]Ramps equipped with rollers.

[5]For exposed locations, loading arms usually allow for 5.0-meter motion.

Table 10
Recommended Practical Motion Criteria
for Moored Vessels (Continued)

(c) Recommended Velocity Criteria for Safe Mooring Conditions for Fishing Vessels, Coasters, Freighters, Ferries and Ro/Ro Vessels (after PIANC, 1995)

Ship Size(DWT)	Surge (m/s)	Sway (m/s)	Heave (m/s)	Yaw (^{o}/s)	Pitch (^{o}/s)	Roll (^{o}/s)
1000	0.6	0.6	-	2.0	-	2.0
2000	0.4	0.4	-	1.5	-	1.5
8000	0.3	0.3	-	1.0	-	1.0

(d) Special Criteria for Walkways and Rail Ramps (after PIANC, 1995)

Parameter	Maximum Value
Vertical velocity	0.2 m/s
Vertical acceleration	0.5 m/s^2

Table 10
Recommended Practical Motion Criteria
for Moored Vessels (Continued)

(e) Special Criteria

CONDITION	MAXIMUM VALUES	NOTES
Heave	-	Ships will move vertically with any long period water level change (tide, storm surge, flood, etc.). The resulting buoyancy forces may be high, so the mooring must be designed to provide for these motions due to long period water level changes.
Loading/unloading preposition ships	0.6 m (2 feet)	Maximum ramp motion during loading/unloading moving wheeled vehicles.
Weapons loading/unloading	0.6 m (2 feet)	Maximum motion between the crane and the object being loaded/unloaded.

3.3 Design Methods

3.3.1 Quasi-Static Design. Practical experience has shown that in many situations such as for Mooring Service Types I and II, static analysis tools can be used to reliably determine mooring designs in harbors. Winds are a key forcing factor in mooring harbors. Winds can be highly dynamic in heavy weather conditions. However, practical experience has shown that for typical DOD ships, a wind speed with a duration of 30 seconds can be used, together with static tools, to develop safe mooring designs. The use of the 30-second duration wind speed with static tools and the approach shown in Table 11 is called “quasi-static” design.

Table 11
Quasi-Static Design Notes

CRITERIA	NOTES
Wind speed	Determine for the selected return interval, R. For typical ships use the wind that has a duration of 30 seconds at an elevation of 10 m.
Wind direction	Assume the wind can come from any direction except in cases where wind data show extreme winds occur in a window of directions.
Current speed	Use conditions for the site (speed and direction).
Water levels	Use the range for the site.
Waves	Neglected. If waves are believed to be important, then dynamic analyses are recommended.
Factors of safety	Perform the design using quasi-static forces and moments (see Section 4), minimum factors of safety in Table 9, and design to assure that all criteria are met.

3.3.2 Dynamic Mooring Analysis. Conditions during Mooring Service Types III and IV, and during extreme events can be highly dynamic. Unfortunately, the dynamic behavior of a moored ship in shallow water can be highly complex, so dynamics cannot be fully documented in this handbook. An introduction to dynamics is provided in Section 8. Information on dynamics is found in: Dynamic Analysis of Moored Floating Drydocks, Headland et. al. (1989); Advanced Dynamics of Marine Structures, Hooft (1982); Hydrodynamic Analysis and Computer Simulation Applied to Ship Interaction During Maneuvering in Shallow Channels, Kizakkevariath (1989); David Taylor Research Center (DTRC), SPD-0936-01, User's Manual for the Standard Ship Motion Program, SMP81; Low Frequency Second Order Wave Exciting Forces on Floating Structures, Pinkster (1982); Mooring Dynamics Due to Wind Gust Fronts, Seelig and Headland (1998); and A Simulation Model for a Single Point Moored Tanker, Wichers (1988). Some conditions when mooring dynamics may be important to design or when specialized considerations need to be made are given in Table 12.

3.4 Risk. Risk is a concept that is often used to design facilities, because the probability of occurrence of extreme events (currents, waves, tides, storm surge, earthquakes, etc.) is strongly site dependent. Risk is used to ensure that systems are reliable, practical, and economical.

A common way to describe risk is the concept of 'return interval', which is the mean length of time between events. For example, if the wind speed with a return interval of R = 100 years is given for a site, this wind speed would be expected to occur, on the average, once every 100 years. However, since wind speeds are probabilistic, the specified 100-year wind speed might not occur at all in any 100-year period. Or, in any 100-year period the wind speed may be equal to or exceed the specified wind speed multiple times.

The probability or risk that an event will be equaled or exceeded one or more times during any given interval is determined from:

EQUATION: $$P = 100\% * (1-(1-1/R)^N) \qquad (1)$$

where

P = probability, in percent, of an event being equaled or exceeded one or more times in a specified interval
R = return interval (years)
N = service life (years)

Figure 15 shows risk versus years on station for various selected values of return interval. For example, take a ship that is on station at a site for 20 years (N=20). There is a P=18.2 percent probability that an event with a return interval of R=100 years or greater will occur one or more times at a site in a 20-year interval.

Table 12
Conditions Requiring Special Analysis

FACTOR	SPECIAL ANALYSIS REQUIRED
Wind	> 45 mph for small craft > 75 mph for larger vessels
Wind waves	> 1.5 ft for small craft > 4 ft for larger vessels
Wind gust fronts	Yes for SPMs
Current	> 3 knots
Ship waves and passing ship effects	Yes for special cases (see Kizakkevariath, 1989; Occasion, 1996; Weggel and Sorensen, 1984 & 1986)
Long waves (seiches and tidal waves or tsunamis)	Yes
Berthing and using mooring as a break	Yes (see MIL-HDBK-1025/1)
Parting tension member	May be static or dynamic
Ship impact or other sudden force on the ship	Yes (if directed)
Earthquakes (spud moored or stiff systems)	Yes
Explosion, landslide, impact	Yes (if directed)
Tornado (reference NUREG 1974)	Yes
Flood, sudden water level rise	Yes (if directed)
Ice forcing	Yes (if a factor)
Ship/mooring system dynamically unstable (e.g., SPM)	Yes (dynamic behavior of ships at SPMs can be especially complex)
Forcing period near a natural period of the mooring system	Yes; if the forcing period is from 80% to 120% of a system natural period

Note: SPM = single point mooring

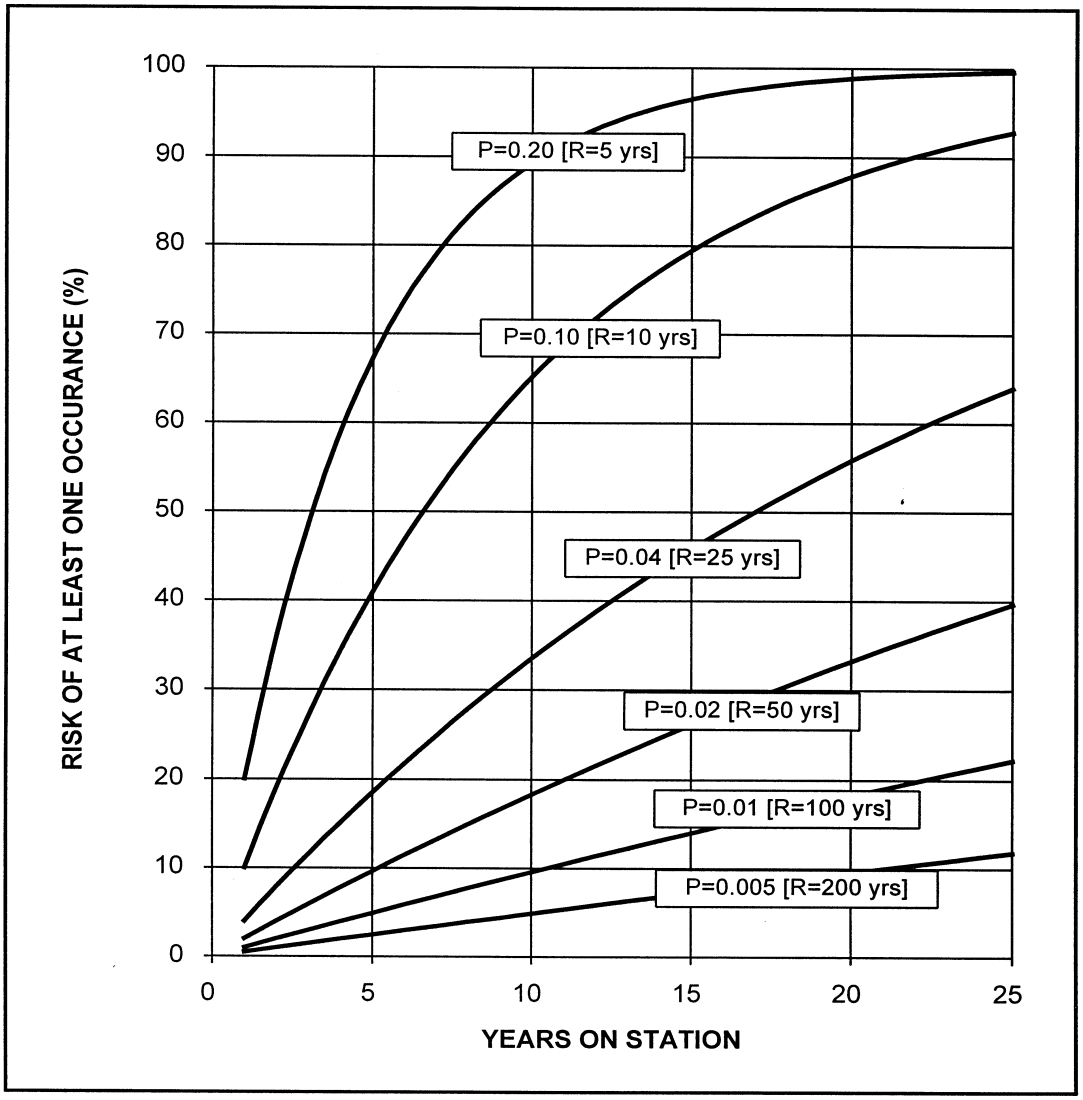


Figure 15

Risk Diagram

3.5 Coordinate Systems. The various coordinate systems used for ships and mooring design are described below.

3.5.1 Ship Design/Construction Coordinates. A forward perpendicular point (FP), aft perpendicular point (AP), and regular spaced frames along the longitudinal axes of the ship are used to define stations. The bottom of the ship keel is usually used as the reference point or “baseline” for vertical distances. Figure 16 illustrates ship design coordinates.

3.5.2 Ship Hydrostatics/Hydrodynamics Coordinates. The forward perpendicular is taken as Station 0, the aft perpendicular is taken as Station 20, and various cross-sections of the ship hull (perpendicular to the longitudinal axis of the ship) are used to describe the shape of the ship hull. Figure 16 illustrates ship hydrostatic conventions.

3.5.3 Local Mooring Coordinate System. Environmental forces on ships are a function of angle relative to the vessel’s longitudinal centerline. Also, a ship tends to move about its center of gravity. Therefore, the local “right-hand-rule” coordinate system, shown in Figure 17, is used in this handbook. The midship’s point is shown as a convenient reference point in Figures 17 and 18.

3.5.4 Global Coordinate System. Plane state grids or other systems are often used to describe x and y coordinates. The vertical datum is most often taken as relative to some water level, such as mean lower low water (MLLW).

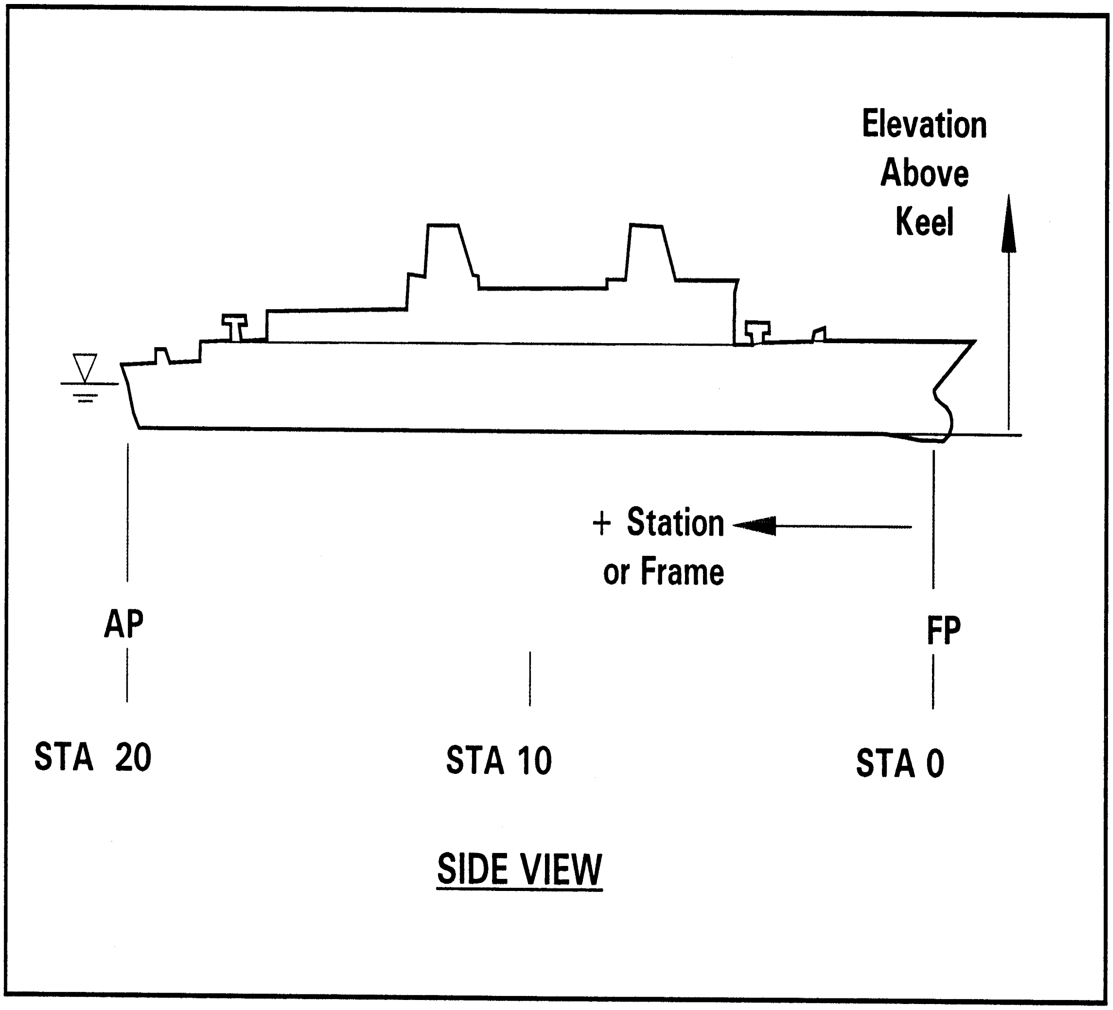


Figure 16

Ship Design and Hydrostatic Coordinates

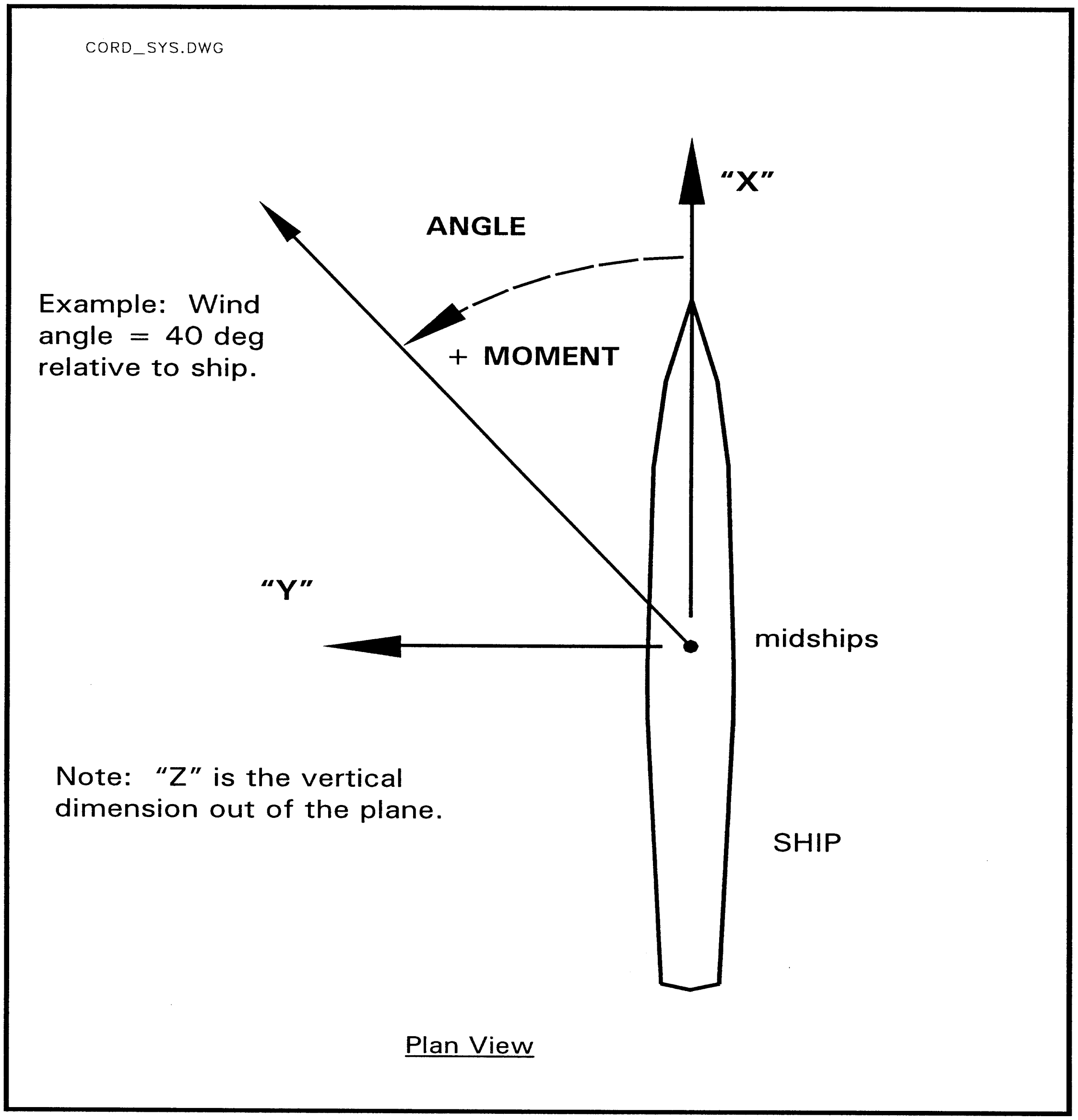


Figure 17
Local Mooring Coordinate System for a Ship

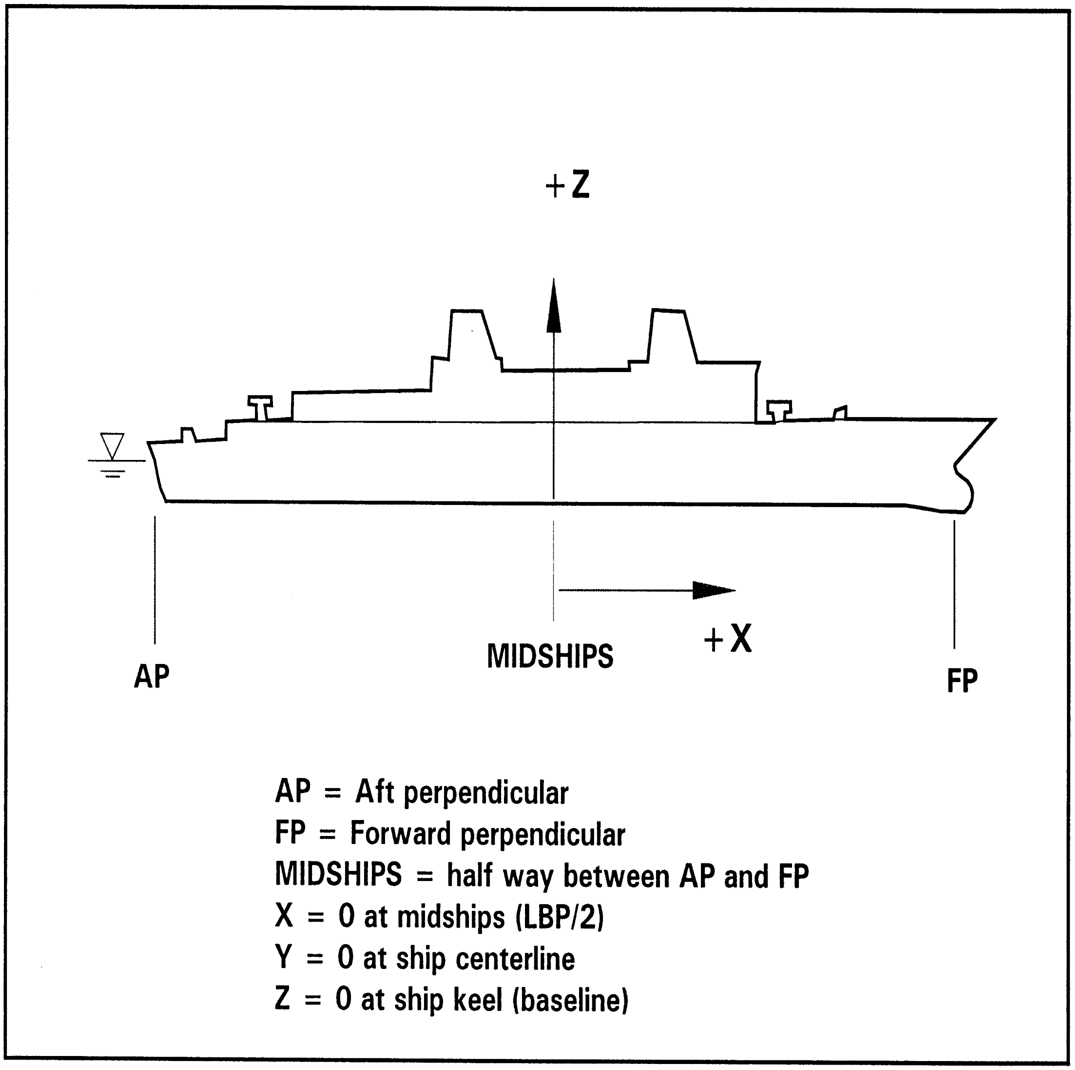


Figure 18
Local Mooring Coordinate System for a Ship

3.6 Vessel Design Considerations. Some important vessel mooring design considerations are summarized in Table 13.

Table 13
Design Considerations - Ship

PARAMETER	NOTES
Ship fittings	The type, capacity, location, and number of mooring fittings on the ship are critical in designing moorings.
Ship hardware	The type, capacity, location, and number of other mooring hardware (chain, anchors, winches, etc.) on the ship are critical.
Buoyancy	The ship's buoyancy supports the ship up in the heave, pitch, and roll directions. Therefore, it is usually undesirable to have much mooring capacity in these directions. A large ship, for example, may have over a million pounds of buoyancy for a foot of water level rise. If an unusually large water level rise occurs for a mooring with a large component of the mooring force in the vertical direction, this could result in mooring failure.
Hull pressures	Ships are designed so that only a certain allowable pressure can be safely resisted. Allowable hull pressures and fender design are discussed in Appendix B.

3.7 Facility Design Considerations. Some important facility mooring design considerations are summarized in Table 14.

Table 14
Design Considerations - Facility

PARAMETER	NOTES
Access	Adequate ship access in terms of channels, turning basins, bridge clearance, etc. needs to be provided. Also, tugs and pilots must be available.
Mooring fittings	The number, type, location and capacity of mooring fittings or attachment point have to meet the needs of all vessels using the facility.
Fenders	The number, type, location, and properties of marine fenders must be specified to protect the ship(s) and facility.
Water depth	The water depth at the mooring site must be adequate to meet the customer’s needs.
Shoaling	Many harbor sites experience shoaling. The shoaling and possible need for dredging needs to be considered.
Permits	Permits (Federal, state, environmental, historical, etc.) are often required for facilities and they need to be considered.

3.8 Environmental Forcing Design Considerations. Environmental forces acting on a moored ship(s) can be complex. Winds, currents, water levels, and waves are especially important for many designs.

3.8.1 Winds. A change in pressure from one point on the earth to another causes the wind to blow. Turbulence is carried along with the overall wind flow to produce wind gusts. If the mean wind speed and direction do not change very rapidly with time, the winds are referred to as “stationary.”

Practical experience has shown that wind gusts with a duration of approximately 30 seconds or longer have a significant influence on typical moored ships with displacements of about 1000 tons or larger. Vessels with shorter natural periods can respond to shorter duration gusts. For the purposes of this handbook, a 30-second wind duration at a 10-meter (33-foot) elevation is recommended for the design for “stationary” winds. The relationship of the 30-second wind to other wind durations is shown in Figure 19.

If wind speed and/or direction changes rapidly, such as in a wind gust front, hurricane or tornado, then winds are “non-stationary”. Figure 20, for example, shows a recording from typhoon OMAR on Guam. The eye of this storm went over the recording site. The upper portion of this figure shows the wind speed and the lower portion of the figure is the wind direction. Time on the chart recorder proceeds from right to left. This hurricane had rapid changes in wind speed and direction. As the eye passes there is also a large scale change in wind speed and direction.

Figure 19
Ratio of Wind Speeds for Various Gusts
(after ASCE 7-95)

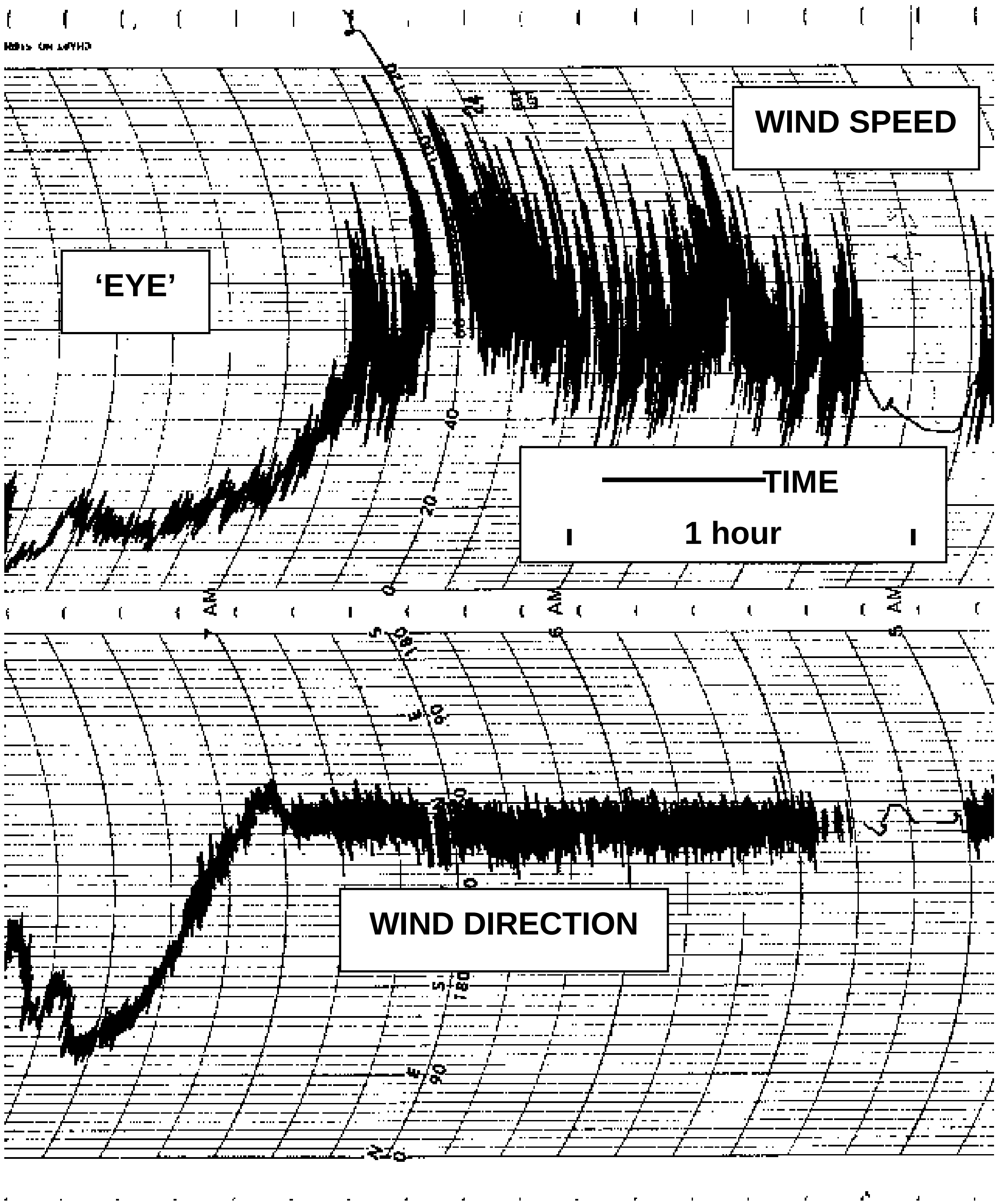


Figure 20
Typhoon *OMAR* Wind Chart Recording

3.8.2 Wind Gust Fronts. A particularly dangerous wind condition that has caused a number of mooring accidents is the wind gust front (Mooring Dynamics Due to Wind Gust Fronts, Seelig and Headland, 1998 and CHESNAVFACENGCOM, FPO-1-87(1), Failure Analysis of Hawsers on BOBO Class MSC Ships at Tinian on 7 December 1986). This is a sudden change in wind speed that is usually associated with a change in wind direction (Wind Effects on Structures, Simiu and Scanlan, 1996). The key problems with this phenomena are: (1) high mooring dynamic loads can be produced in a wind gust front, (2) there is often little warning, (3) little is known about wind gust fronts, and (4) no design criteria for these events have been established.

A study of Guam Agana National Air Station (NAS) wind records was performed to obtain some statistics of wind gust fronts (National Climatic Data Center (NCDC), Letter Report E/CC31:MJC, 1987). The 4.5 years of records analyzed from 1982 through 1986 showed approximately 500 cases of sudden wind speed change, which were associated with a shift in wind direction. These wind shifts predominately occurred in 1 minute or less and never took longer than 2 minutes to reach maximum wind speed. Figure 21 shows sudden changes in wind speed and direction that occurred over a 2-1/2 day period in October 1982. These wind gust fronts seemed to be associated with a nearby typhoon.

Table 15 gives the joint distribution of wind shifts in terms of the amount the increase in wind speed and the wind direction change. Approximately 60 percent of the wind gust fronts from 1982 through 1986 had wind direction changes in the 30-degree range, as shown in Figure 22.

Based on the Guam observations, the initial wind speed in a wind gust front ranges from 0 to 75 percent of the maximum wind speed, as shown in Figure 23. On the average, the initial wind speed was 48 percent of the maximum in the 4.5-year sample from Guam (NCDC, 1987).

Simiu and Scanlan (1996) report wind gust front increases in wind speed ranging from 3 m/sec to 30 m/sec (i.e., 6 to 60 knots). Figure 24 shows the distribution of gust front winds from the 4.5-year sample from 1982 through 1986 on Guam. This figure shows the probability of exceedence on the x-axis in a logarithmic format. The square of the wind gust front speed maximums was plotted on the y-axis, since wind force is proportional to wind speed squared. Figure 24 provides a sample of the maximum wind gust front distribution for a relatively short period at one site. Those wind gust fronts that occurred when a typhoon was nearby are identified with an “H”. It can be seen that the majority of the higher gust front maximums were associated with typhoons. Also, the typhoon gust front wind speed maxima seem to follow a different distribution that the gust front maxima associated with rain and thunderstorms (see Figure 24).

Effects of winds and wind gusts are shown in the examples in Section 8 of this handbook.

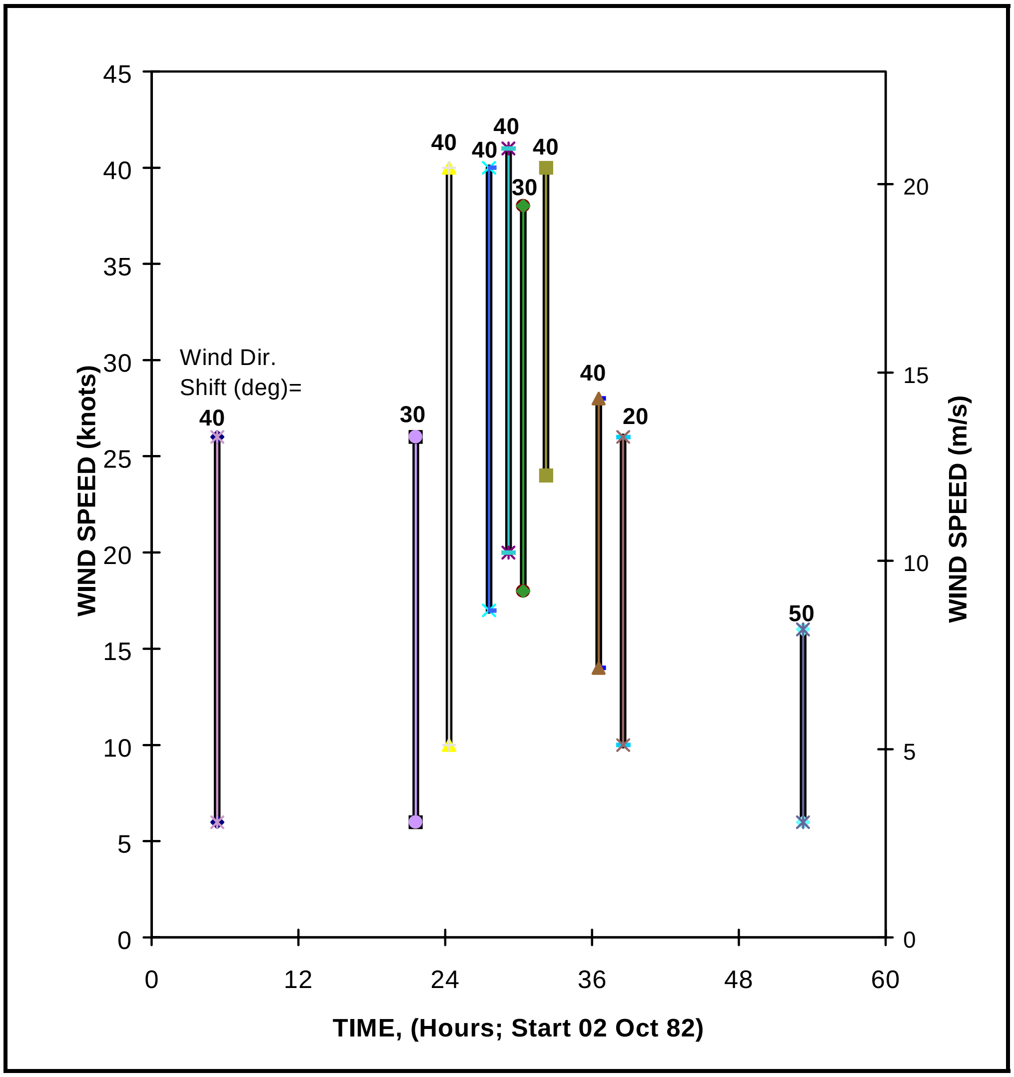


Figure 21
Sample Wind Gust Fronts on Guam, 2-4 October 1982

Table 15. Sample Distribution of Wind Gust Fronts on Guam (Agana NAS) from 1982 to 1986

WIND SPEED CHANGE (knots)		(m/s)		**NUMBER OF OBSERVATIONS** WIND DIRECTION CHANGE							
MIN.	MAX.	MIN.	MAX.	20 deg	30 deg	40 deg	50 deg	60 deg	70 deg	80 deg	90 deg
6	10	3.1	5.1	28	241	66	30	4		2	
11	15	5.7	7.7	8	42	18	13	5	3	1	1
16	20	8.2	10.3	6	7	3	2	2			
21	25	10.8	12.9		3	2		1			
26	30	13.4	15.4			1					

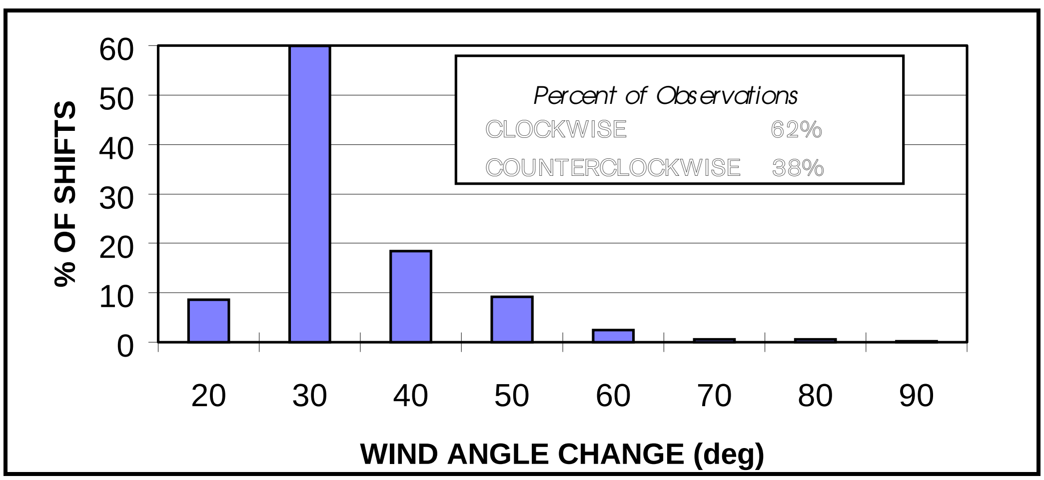
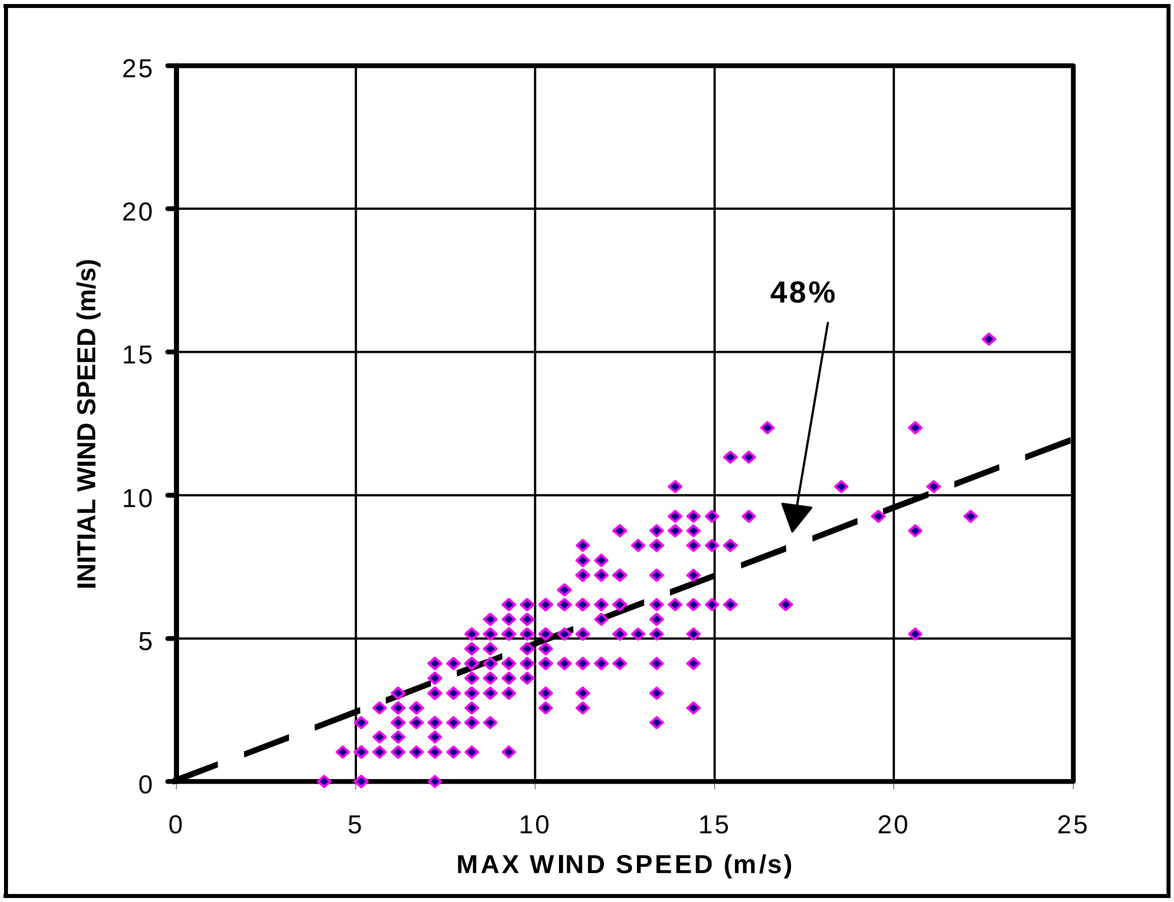


Figure 22
Distribution of Guam Wind Gust Front Wind Angle Changes

Figure 23
Initial Versus Maximum Wind Speeds for Wind Gust Fronts



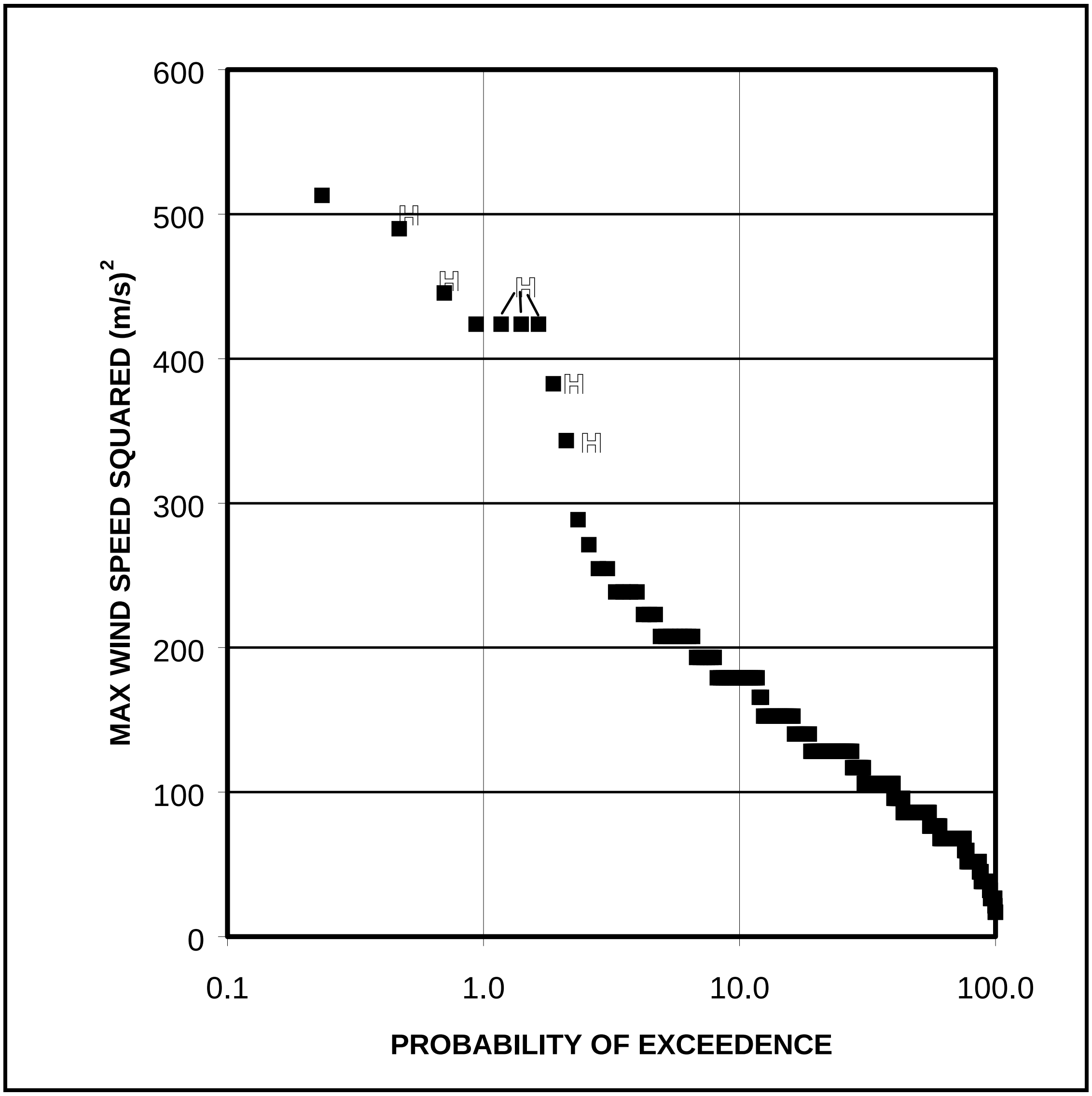


Figure 24
Wind Gust Front Maxima on Guam 1982-1986

3.8.3 Storms. Table 16 gives environmental parameters for standard storms.

Table 16
Storm Parameters

(a) Tropical Storms

STORM	LOWER WIND SPEED (m/s)	(mph)	(knts)	UPPER WIND SPEED (m/s)	(mph)	(knts)
TROPICAL DEPRESSION	10.3	23	20	17	38	33
TROPICAL STORM	18.0	40	35	32.4	74	63
HURRICANE	33.1	74	64	-	-	-

(b) Saffier-Simpson Hurricane Scale

	WIND SPEED RANGE				OPEN COAST STORM SURGE RANGE			
	LOWER		UPPER		LOWER		UPPER	
CATE-GORY	(m/s)	(mph)	(m/s)	(mph)	(m)	(ft)	(m)	(ft)
1	33.1	74	42.5	95	1.22	4	1.52	5
2	42.9	96	49.2	110	1.83	6	2.44	8
3	49.6	111	58.1	130	2.74	9	3.66	12
4	58.6	131	69.3	155	3.96	13	5.49	18
5	69.3	155	-	-	5.49	18	-	-

Table 16
Storm Parameters (Continued)

(c) Beaufort Wind Force*

BEAUFORT WIND FORCE/ DESCRIPTION	LOWER WIND SPEED (m/s)	LOWER WIND SPEED (mph)	LOWER WIND SPEED (knts)	UPPER WIND SPEED (m/s)	UPPER WIND SPEED (mph)	UPPER WIND SPEED (knts)
0 CALM	0.0	0	0	0.5	1	1
1 LIGHT AIRS	0.5	1	1	1.5	4	3
2 LIGHT BREEZE	2.1	5	4	3.1	7	6
3 GENTLE GREEZE	3.6	8	7	5.1	12	10
4 MODERATE BREEZE	5.7	13	11	8.2	18	16
5 FRESH BREEZE	8.8	20	17	10.8	24	21
6 STRONG BREEZE	11.3	25	22	13.9	31	27
7 MODERATE GALE	14.4	32	28	17.0	38	33
8 FRESH GALE	17.5	39	34	20.6	46	40
9 STRONG GALE	21.1	47	41	24.2	54	47
10 WHOLE GALE	24.7	55	48	28.3	63	55
11 STORM	28.8	65	56	32.4	73	63
12 HURRICANE	32.9	74	64	36.6	82	71

*After Handbook of Ocean and Underwater Engineers, Myers et al. (1969).

Table 16
Storm Parameters (Continued)

(d) World Meteorological Organization Sea State Scale

SEA STATE	Sign. Wave Height (ft) [m]	Sustained Wind Speed (knts) [m/s]	Modal Wave Period Range (sec)
0 CALM/GLASSY	NONE	NONE	-
1 RIPPLED	0-0.3 [0-0.1]	0-6 [0-3]	-
2 SMOOTH	0.3-1.6 [0.1-0.5]	7-10 [3.6-5.1]	3-15
3 SLIGHT	1.6-4.1 [0.5-1.2]	11-16 [5.7-8.2]	3-15.5
4 MODERATE	4.1-8.2 [1.2-2.5]	17-21 [8.7-10.8]	6-16
5 ROUGH	8.2-13.1 [2.5-4.0]	22-27 [11.3-13.9]	7-16.5
6 VERY ROUGH	13.1-19.7 [4.0-6.0]	28-47 [14.4-24.2]	9-17
7 HIGH	19.7-29.5 [6.0-9.0]	48-55 [24.7-28.3]	10-18
8 VERY HIGH	29.5-45.5[9.0-13.9]	56-63 [28.8-32.4]	13-19
9 PHENOMENAL	>45.5 [>13.9]	>63 [>32.4]	18-24

3.8.4 Currents. The magnitude and direction of currents in harbors and nearshore areas are in most cases a function of location and time. Astronomical tides, river discharges, wind-driven currents, and other factors can influence currents. For example, wind-driven currents are surface currents that result from the stress exerted by the wind on the sea surface. Wind-driven currents generally attain a mean velocity of about 3 to 5 percent of the mean wind speed at 10 meters (33 feet) above the sea surface. The magnitude of this current strongly decreases with depth.

Currents can be very site specific, so it is recommended that currents be measured at the design site and combined with other information available to define the design current conditions.

3.8.5 Water Levels. At most sites some standard datum, such as mean low water (MLW) or mean lower low water (MLLW), is established by formal methods. Water levels are then referenced to this datum. The water level in most harbors is then a function of time. Factors influencing water levels include astronomical tides, storm surges, river discharges, winds, seiches, and other factors.

The design range in water levels at the site must be considered in the design process.

3.8.6 Waves. Most DOD moorings are wisely located in harbors to help minimize wave effects. However, waves can be important to mooring designs in some cases. The two primary wave categories of interest are:

a) Wind waves. Wind waves can be locally generated or can be wind waves or swell entering the harbor entrance(s). Small vessels are especially susceptible to wind waves.

b) Long waves. These can be due to surf beat, harbor seiching, or other effects.

Ship waves may be important in some cases. The response of a moored vessel to wave forcing includes:

a) A steady mean force.

b) First order response, where the vessel responds to each wave, and

c) Second order response, where some natural long period mode of ship/mooring motion, which usually has little damping, is forced by the group or other nature of the waves.

If any of these effects are important to a given mooring design, then a six-degree-of-freedom dynamic of the system generally needs to be considered in design. Some guidance on safe wave limits is given in Table 9

3.8.7 Water Depths. The bathymetry of a site may be complex, depending on the geology and history of dredging. Water depth may also be a function of time, if there is shoaling or scouring. Water depths are highly site specific, so hydrographic surveys of the project site are recommended.

3.8.8 Environmental Design Information. Some sources of environmental design information of interest to mooring designers are summarized in Table 17.

Table 17
Some Sources of Environmental Design Information

a. Winds

NAVFAC Climate Database, 1998
ANSI/ASCE 7-95 (1996)
National Bureau of Standards (NBS), Series 124, Hurricane Wind Speeds in the United States, 1980
Nuclear Regulatory Commission (NUREG), NUREG/CR-2639, Historical Extreme Winds for the United States – Atlantic and Gulf of Mexico Coastlines, 1982
Hurricane and typhoon havens handbooks, NRL (1996) and NEPRF (1982)
NUREG/CR-4801, Climatology of Extreme Winds in Southern California, 1987
NBS Series 118, Extreme Wind Speeds at 129 Stations in the Contiguous United States, 1979

b. Currents

NAVFAC Climate Database, 1998
National Ocean Survey records
Nautical Software, Tides and Currents for Windows, 1995
U.S. Army Corps of Engineers records

Table 17
Some Sources of Environmental Design Information (Continued)

c. Water Levels

NAVFAC Climate Database, 1998
Federal Emergency Management Agency records
U.S. Army Corps of Engineers, Special Report No. 7, Tides and Tidal Datums in the United States, 1981
National Ocean Survey records
Hurricane and typhoon havens handbooks, NRL (1996) and NEPRF (1982)
Nautical Software (1995)
U.S. Army Corps of Engineers records

d. Waves

Hurricane and typhoon havens handbooks, NRL (1996) and NEPRF (1982)
U.S. Army Corps of Engineers, Shore Protection Manual (1984) gives prediction methods

e. Bathymetry

From other projects in the area
National Ocean Survey charts and surveys
U.S. Army Corps of Engineers dredging records

3.9 Operational Considerations. Some important operational design considerations are summarized in Table 18.

Table 18
Mooring Operational Design Considerations

PARAMETER	NOTES
Personnel experience/ training	What is the skill of the people using the mooring?
Failure	What are the consequences of failure? Are there any design features that can be incorporated that can reduce the impact?
Ease of use	How easy is the mooring to use and are there factors that can make it easier to use?
Safety	Can features be incorporated to make the mooring safer for the ship and personnel?
Act-of-God events	Extreme events can occur unexpectedly. Can features be incorporated to accommodate them?
Future use	Future customer requirements may vary from present needs. Are there things that can be done to make a mooring facility more universal?

3.10 Inspection. Mooring systems and components should be inspected periodically to ensure they are in good working order and are safe. Table 19 gives inspection guidelines.

Table 19
Inspection Guidelines

MOORING SYSTEM OR COMPONENT	MAXIMUM INSPECTION INTERVAL	NOTES
Piers and wharves	1 year 3 years 6 years	Surface inspection Complete inspection - wood structures Complete inspection - concrete and steel structures See NAVFAC MO-104.2, Specialized Underwater Waterfront Facilities Inspections; If the actual capacity/condition of mooring fittings on a pier/wharf is unknown, then pull tests are recommended to proof the fittings.
Fleet Moorings	3 years	See CHESNAVFACENGCOM, FPO-1-84(6), Fleet Mooring Underwater Inspection Guidelines. Also inspect and replace anodes, if required. More frequent inspection may be required for moorings at exposed sites or for critical facilities.
Synthetic line	6 months	Per manufacturer's recommendations

Table 19
Inspection Guidelines (Continued)

MOORING SYSTEM OR COMPONENT	MAXIMUM INSPECTION INTERVAL	NOTES
Ship's chain	36 months	0-3 years of service
	24 months	4-10 years of service
	18 months	>10 years of service
		(American Petroleum Institute (API) RP 2T, Recommended Practice for Planning, Designing, and Constructing Tension Leg Platforms)
Wire rope	18 months	0-2 years of service
	12 months	3-5 years of service
	9 months	>5 years of service
		(API RP 2T)

3.11 Maintenance. If excessive wear or damage occurs to a mooring system, then it must be maintained. Fleet mooring chain, for example, is allowed to wear to a diameter of 90 percent of the original steel bar diameter. As measured diameters approach 90 percent, then maintenance is scheduled. Moorings with 80 to 90 percent of the original chain diameter are restricted to limited use. If a chain diameter reaches a bar diameter of 80 percent of the original diameter, then the mooring is condemned. Figure 25 illustrates some idealized models of chain wear

3.12 General Mooring Guidelines. Experience and practical considerations show that the recommendations given in Table 20 will help ensure safe mooring. These ideas apply to both ship mooring hardware and mooring facilities.

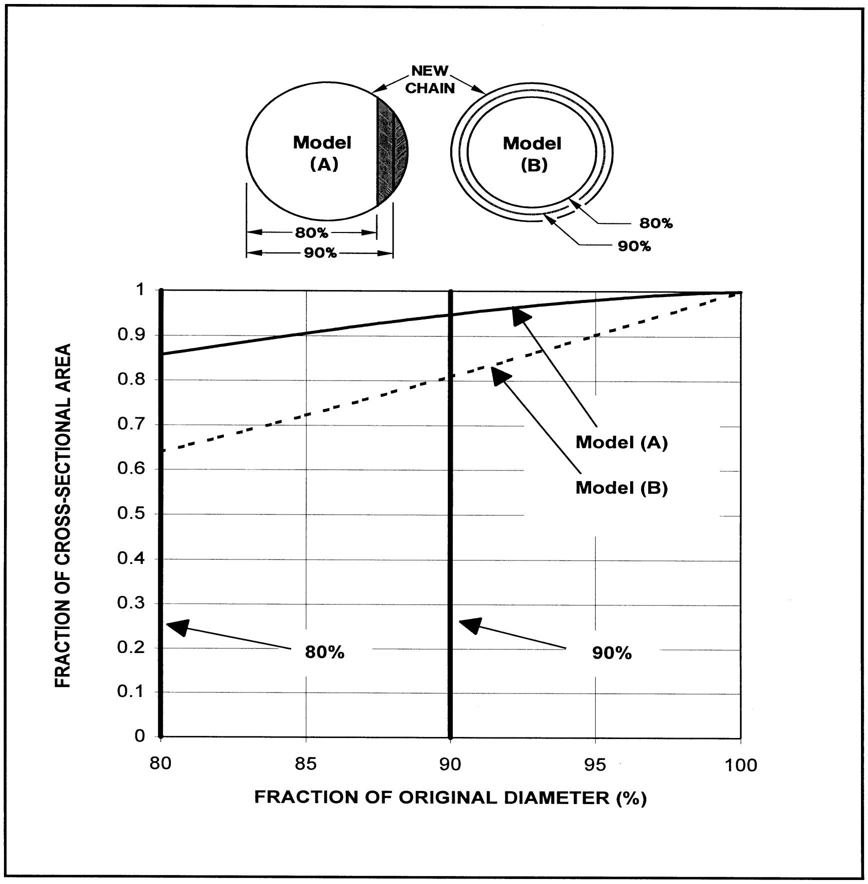


Figure 25
Idealized Models of Chain Wear

Table 20
Design Recommendations

IDEA	NOTES
Allow ship to move with rising and falling water levels	The weight and buoyancy forces of ships can be very high, so it is most practical to design moorings to allow ships to move in the vertical direction with changing water levels. The design range of water levels for a specific site should be determined in the design process.
Ensure mooring system components have similar strength	A system is only as strong as its weakest segment; a system with components of similar strength can be the most economical. Mooring lines should not have a break strength greater than the capacity of the fittings they use.
Ensure load sharing	In some moorings, such as at a pier, many lines are involved. Ensuring that members will share the load results in the most economical system.
Bridle design	In cases where a ship is moored to a single point mooring buoy with a bridle, ensure that each leg of the bridle can withstand the full mooring load, because one member may take the full load as the vessel swings.
Provide shock absorbing in mooring systems	Wind gusts, waves, passing ships, etc., will produce transient forces on a moored ship. Allowing some motion of the ship will reduce the dynamic loads. ‘Shock absorbers’ including marine fenders, timber piles, synthetic lines with stretch, chain catenaries, sinkers, and similar systems are recommended to allow a moored ship to move in a controlled manner.

Table 20
Design Recommendations (Continued)

IDEA	NOTES
Limit the vertical angles of lines from ship to pier	Designing ships and piers to keep small vertical line angles has the advantages of improving line efficiency and reducing the possibility of lines pulling off pier fittings.
Select drag anchors to have a lower ultimate holding capacity than the breaking strength of chain and fittings	Design mooring system that uses drag anchor, so that the anchor will drag before the chain breaks.
Limit the loading on drag anchors to horizontal tension	Drag anchors work on the principle of 'plowing' into the soils. Keeping the mooring catenary angle small at the seafloor will aid in anchor holding. Have at least one shot of chain on the seafloor to help ensure the anchor will hold.
Pull test anchors whenever possible to the full design load	Pull testing anchors is recommended to ensure that all facilities with anchors provide the required holding capacity.

Section 4: STATIC ENVIRONMENTAL FORCES AND MOMENTS ON VESSELS

4.1 Scope. In this section design methods are presented for calculating static forces and moments on single and multiple moored vessels. Examples show calculation methods.

4.2 Engineering Properties of Water and Air. The effects of water and air at the surface of the earth are of primary interest in this section. The engineering properties of both are given in Table 21.

Table 21
Engineering Properties of Air and Water

(a) Standard Salt Water
at Sea Level at 15°C (59°F)

PROPERTY	SI SYSTEM	ENGLISH SYSTEM
Mass density, $_w$	1026 kg/m^3	1.9905 slug/ft^3
Weight density, $_w$	10060 newton/m^3	64.043 lbf/ft^3
Volume per long ton (LT)	0.9904 m^3/LT	34.977 ft^3/LT
Kinematic viscosity,	1.191E-6 m^2/sec	1.2817E-5 ft^2/sec

(b) Standard Fresh Water
at Sea Level at 15°C (59°F)

PROPERTY	SI SYSTEM	ENGLISH OR INCH-POUND SYSTEM
Mass density, $_w$	999.0 kg/m^3	1.9384 slug/ft^3
Weight density, $_w$	9797 newton/m^3	62.366 lbf/ft^3
Volume per long ton (LT)	1.0171 m^3/LT	35.917 ft^3/LT
Volume per metric ton (ton or 1000 kg or 1 Mg)	1.001 m^3/ton	35.3497 ft^3/ton
Kinematic viscosity,	1.141E-6 m^2/sec	1.2285E-5 ft^2/sec

Table 21
Engineering Properties of Air and Water (Continued)

(c) Air
at Sea Level at 20^{o}C (68^{o}F)*

PROPERTY	SI SYSTEM	ENGLISH OR INCH-POUND SYSTEM
Mass density, $_a$	1.221 kg/m^3	0.00237 slug/ft^3
Weight density, $_a$	11.978 newton/m^3	0.07625 lbf/ft^3
Kinematic viscosity,	1.50E-5 m^2/sec	1.615E-4 ft^2/sec

* Note that humidity and even heavy rain has relatively little effect on the engineering properties of air (personal communication with the National Weather Service, 1996)

4.3 Principal Coordinate Directions. There are three primary axes for a ship:

X - Direction parallel with the ship's longitudinal axis
Y - Direction perpendicular to a vertical plane through the ship's longitudinal axis
Z - Direction perpendicular to a plane formed by the "X" and "Y" axes

There are six principal coordinate directions for a ship:

Surge - In the "X"-direction
Sway - In the "Y"-direction
Heave - In the "Z"-direction
Roll - Angular about the "X"-axis
Pitch - Angular about the "Y"-axis
Yaw - Angular about the "Z"-axis

Of primary interest are: (1) forces in the surge and sway directions in the "X-Y" plane, and (2) moment in the yaw direction about the "Z"-axis. Ship motions occur about the center of gravity of the ship.

4.4 Static Wind Forces/Moments. Static wind forces and moments on stationary moored vessels are computed in this section. Figure 26 shows the definition of some of the terms used in this section. Figure 27 shows the local coordinate system.

4.4.1 Static Transverse Wind Force. The static transverse wind force is defined as that component of force perpendicular to the vessel centerline. In the local ship coordinate system, this is the force in the "Y" or sway direction. Transverse wind force is determined from the equation:

EQUATION: $$F_{yw} = 0.5\,\rho_a\, V_w^2\, A_y\, C_{yw}\, f_{yw}\{\theta_w\} \qquad (2)$$

where

F_{yw} = transverse wind force (newtons)
ρ_a = mass density of air (from Table 20)
V_w = wind speed (m/s)
A_y = longitudinal projected area of the ship (m^2)
C_{yw} = transverse wind force drag coefficient
$f_{yw}\{\theta_w\}$ = shape function for transverse force
θ_w = wind angle (degrees)

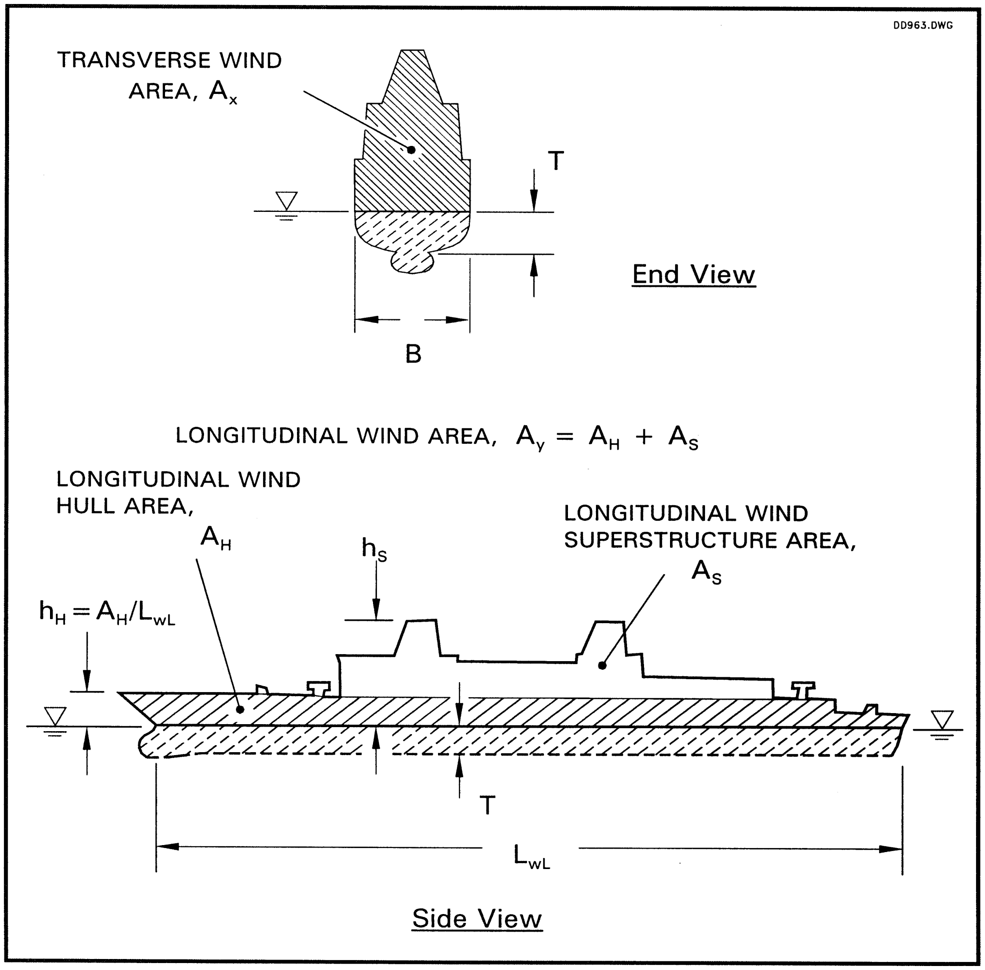


Figure 26
Definition of Terms

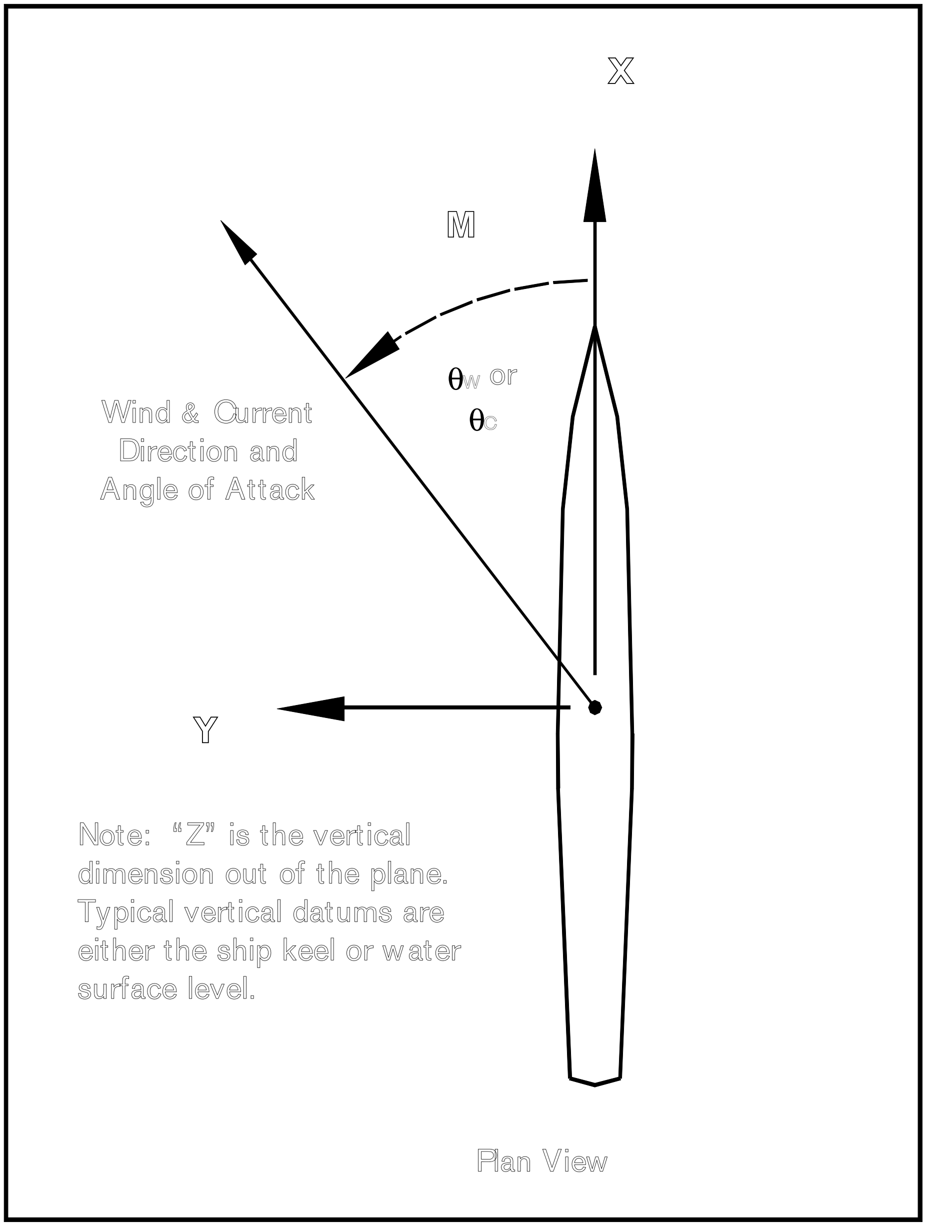


Figure 27
Local Coordinate System for a Ship

The transverse wind force drag coefficient depends upon the hull and superstructure of the vessel and is calculated using the following equation, adapted from Naval Civil Engineering Laboratory (NCEL), TN-1628, Wind-Induced Steady Loads on Ships.

EQUATION: $$C_{yw} = C*\left[((0.5(h_S + h_H)) / h_R)^{2/7} A_S + (0.5*h_H / h_R)^{2/7} A_H\right] / A_Y \qquad (3)$$

where

C_{yw} =		transverse wind force drag coefficient
C =		empirical coefficient, see Table 22
h_R =	10 m	= reference height (32.8 ft)
h_H	$= A_H / L_{wL}$	= average height of the hull, defined as the longitudinal wind hull area divided by the ship length at the waterline (m)
A_H =		longitudinal wind area of the hull (m^2)
L_{wL} =		ship length at the waterline (m)
h_S =		height of the superstructure above the waterline(m)
A_S =		longitudinal wind area of the superstructure (m^2)

A recommended value for the empirical coefficient is C = 0.92 +/-0.1 based on scale model wind tunnel tests (NCEL, TN-1628). Table 22 gives typical values of C for ships and Figure 28 illustrates some ship types.

Table 22

Sample Wind Coefficients for Ships

SHIP	C	NOTES
Hull dominated	0.82	Aircraft carriers, drydocks
Typical	0.92	ships with moderate superstructure
Extensive superstructure	1.02	Destroyers, cruisers

The shape function for the transverse wind force (NCEL, TN-1628) is given by:

EQUATION: $$f_{yw}\{\theta_w\} = +(\sin\theta_w - 0.05 * \sin\{5\theta_w\}) / 0.95 \qquad (4)$$

where

$f_{yw}\{\theta_w\}$ = transverse wind coefficient shape function

θ_w = wind angle (degrees)

Equation 4 is positive for wind angles 0 < w < 180 degrees and negative for wind angles 180 < w < 360 degrees. Figure 29 shows the shape and typical values for Equation 4.

These two components were derived by integrating wind over the hull and superstructure areas to obtain effective wind speeds (NCEL, TN-1628). The following example illustrates calculations of the transverse wind force drag coefficient.

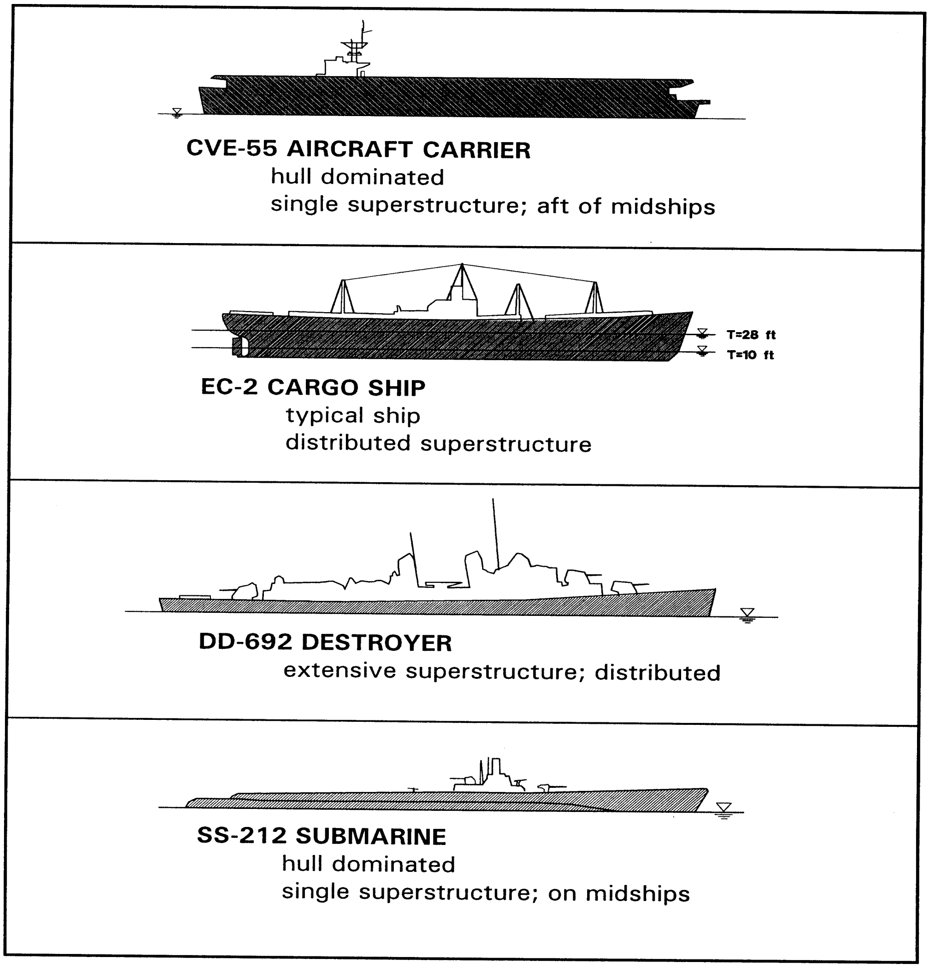


Figure 28
Sample Ship Profiles

θ_w (deg)	$f_{wy}\{\theta_w\}$		θ_w (deg)	$f_{wy}\{\theta_w\}$
0	0.000		45	0.782
5	0.069		50	0.856
10	0.142		55	0.915
15	0.222		60	0.957
20	0.308		65	0.984
25	0.402		70	0.998
30	0.500		75	1.003
35	0.599		80	1.003
40	0.695		85	1.001
45	0.782		90	1.000

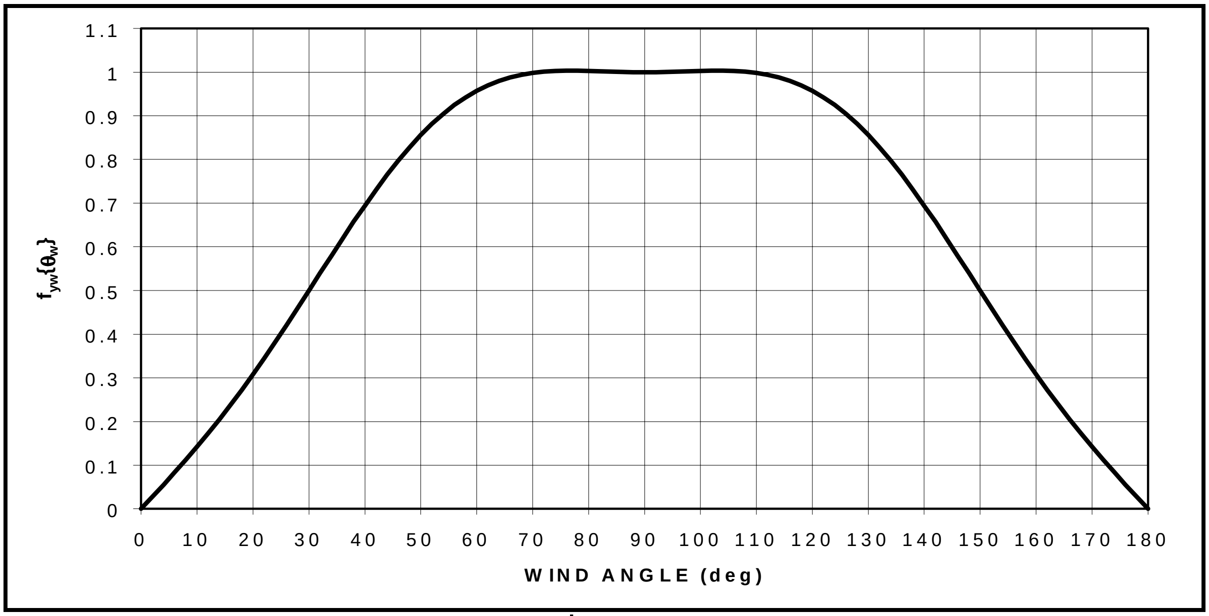


Figure 29
Shape Function for Transverse Wind Force

EXAMPLE: Find the transverse wind force drag coefficient on the destroyer shown in Figure 30.

SOLUTION: For this example the transverse wind force drag coefficient from Equation 3 is:

$$C_{yw} = C * \left[((0.5(23.9m + 6.43m)) / 10m)^{2/7} 1203m^2 + (0.5 * 6.43m / 10m)^{2/7} 1036.1m^2 \right] / 2239m^2$$

$$C_{yw} = 0.940 * C .$$

Destroyers have extensive superstructure, so a recommended value of C = 1.02 is used to give a transverse wind force drag coefficient of C_{yw} = 0.940*1.02 = 0.958.

Note that for cases where an impermeable structure, such as a wharf, is immediately next to the moored ship, the exposed longitudinal wind area and resulting transverse wind force can be reduced. Figure 31 shows an example of a ship next to a wharf. For Case (A), wind from the water, there is no blockage in the transverse wind force and elevations of the hull and superstructure are measured from the water surface. For Case (B), wind from land, the longitudinal wind area of the hull can be reduced by the blocked amount and elevations of hull and superstructure can be measured from the wharf elevation.

Cases of multiple ships are covered in Section 4.6.

Figure 30
Example

4.4.2 Static Longitudinal Wind Force. The static longitudinal wind force on a vessel is defined as that component of wind force parallel to the centerline of the vessel. This is the force in the “X” or surge direction in Figure 27. Figure 26 shows the definition of winds areas.

The longitudinal force is determined from NCEL, TN-1628 using the equation:

EQUATION:

$$F_{xw} = 0.5\,\rho_a\,V_w^{\,2} A_x\,C_{xw}\,f_{xw}(\theta_w) \qquad (5)$$

where

F_{xw} = longitudinal wind force (newtons)
ρ_a = mass density of air (from Table 21)
V_w = wind speed (m/s)
A_x = transverse wind area of the ship (m^2)
C_{xw} = longitudinal wind force drag coefficient
$f_{xw}(\theta_w)$ = shape function for longitudinal force
θ_w = wind angle (degrees)

The longitudinal wind force drag coefficient, C_{xw}, depends on specific characteristics of the vessel. Additionally, the wind force drag coefficient varies depending on bow (C_{xwB}) or stern (C_{xwS}) wind loading. Types of vessels are given in three classes: hull dominated, normal, and excessive superstructure. Recommended values of longitudinal wind force drag coefficients are given in Table 23.

Table 23

Recommended Ship Longitudinal Wind Force Drag Coefficients

VESSEL TYPE	C_{xwB}	C_{xwS}
Hull Dominated (aircraft carriers, submarines, passenger liners)	0.40	0.40
Normal*	0.70	0.60
Center-Island Tankers*	0.80	0.60
Significant Superstructure (destroyers, cruisers)	0.70	0.80

*An adjustment of up to +0.10 to C_{xwB} and C_{xwS} should be made to account for significant cargo or cluttered decks.

The longitudinal shape function also varies over the bow and stern wind loading regions. As the wind direction varies from headwind to tailwind, there is an angle at which the force changes sign. This is defined as θ_x and is dependent on the location of the superstructure relative to midships. Recommended values of this angle are given in Table 24.

Table 24

Recommended Values of θ_x

LOCATION OF SUPERSTRUCTURE	θ_x (deg)
Just forward of midships	100
On midships	90
Aft of midships (tankers)	80
Warships	70
Hull dominated	60

Shape functions are given for general vessel categories below:

CASE I SINGLE DISTINCT SUPERSTRUCTURE

The shape function for longitudinal wind load for ships with single, distinct superstructures and hull-dominated ships is given below (examples include aircraft carriers, EC-2, and cargo vessels):

EQUATION: $$f_{xw}(\theta_w) = \cos(\phi) \qquad (6)$$

where $$\phi_{-} = \left(\frac{90^\circ}{\theta_x}\right)\theta_w \quad \text{for } \theta_w < \theta_x \qquad (6a)$$

$$\phi_{+} = \left(\frac{90^\circ}{180^\circ - \theta_x}\right)(\theta_w - \theta_x) + 90^\circ \quad \text{for } \theta_w > \theta_x \qquad (6b)$$

θ_x = incident wind angle that produces no net longitudinal force (Table 24)

θ_w = wind angle

Values of $f_{xw}(\theta_w)$ are symmetrical about the longitudinal axis of the vessel. So when $\theta_w > 180^\circ$, use $360^\circ - \theta_w$ as θ_w in determining the shape function.

CASE II DISTRIBUTED SUPERSTRUCTURE

EQUATION: $$f_{xw}(\theta_w) = \frac{\left(\sin(\gamma) - \dfrac{\sin(5\gamma)}{10}\right)}{0.9} \qquad (7)$$

where $$\gamma_{-} = \left(\frac{90^\circ}{\theta_x}\right)\theta_w + 90^\circ \quad \text{for } \theta_w < \theta_x \qquad (7a)$$

$$\gamma_{+} = \left(\frac{90^\circ}{180^\circ - \theta_x}\right)(\theta_w) + \left(180^\circ - \left(\frac{90^\circ \theta_x}{180^\circ - \theta_x}\right)\right) \quad \text{for } \theta_w > \theta_x \qquad (7b)$$

Values of $f_{xw}(\theta_w)$ are symmetrical about the longitudinal axis of the vessel. So when $\theta_w > 180^\circ$, use $360^\circ - \theta_w$ as θ_w in determining the shape function. Note that the maximum longitudinal wind force for these vessels occurs for wind directions slightly off the ship's longitudinal axis.

EXAMPLE: Find the longitudinal wind drag coefficient for a wind angle of 40 degrees for the destroyer shown in Figure 30.

SOLUTION: For this destroyer, the following values are selected:

θ_x = 70^o from Table 24

C_{xwB} = 0.70 from Table 23

C_{xwS} = 0.80 from Table 23

This ship has a distributed superstructure and the wind angle is less than the crossing value, so Equation 7a is used to determine the shape function:

$$\gamma\_ = \left(90^o / (70^o)\right)40^o + 90^o = 141.4^o$$

$$f_{xw}\ (\theta_w\ ) = \frac{\left(\sin\left(141.4^{\,o}\right) - \dfrac{\sin(5 * 141.4^{\,o})}{10}\right)}{0.9} = 0.72$$

At the wind angle of 40 degrees, the wind has a longitudinal component on the stern. Therefore, the wind longitudinal drag coefficient for this example is:

$$C_{xw}\ f_{xw}\ (\theta_w\ ) = 0.8 * 0.72 = 0.57$$

4.4.3 <u>Static Wind Yaw Moment</u>. The static wind yaw moment is defined as the product of the associated transverse wind force and its distance from the vessel's center of gravity. In the local ship coordinate system, this is the moment about the "Z" axis. Wind yaw moment is determined from the equation:

EQUATION: $$M_{\mathrm{xyw}} = 0.5\,\rho_{\mathrm{a}}\ \mathrm{V_w}^{2}\ \mathrm{A_y}\ \mathrm{L}\mathrm{C_{xyw}}\left\{\theta_{\mathrm{w}}\right\} \qquad (8)$$

where

M_{xyw} =	wind yaw moment (newton*m)
ρ_{a} =	mass density of air (from Table 21)
$\mathrm{V_w}$ =	wind speed (m/s)
$\mathrm{A_y}$ =	longitudinal projected area of the ship (m^2)
L =	length of ship (m)
$\mathrm{C_{xyw}}\left\{\theta_{\mathrm{w}}\right\}$ =	normalized yaw moment coefficient = moment arm divided by ship length
θ_{w} =	wind angle (degrees)

The normalized yaw moment coefficient depends upon the vessel type. Equation 9 gives equations for computing the value of the yaw moment coefficient and Table 25 gives empirical parameter values for selected vessel types. The normalized yaw moment variables is found from:

EQUATION: $$C_{xyw}\{\theta_{\mathrm{w}}\} = -\mathrm{a1} * \sin\left(\frac{\theta_w * 180}{\theta_z}\right) \qquad 0<{}_{w}<{}_{z} \qquad (9)$$

$$C_{xyw}\{\theta_{\mathrm{w}}\} = \mathrm{a2} * \sin\left[(\theta_{\mathrm{w}} - \theta_z) * \lambda)\right] \qquad {}_{z}\ {}_{w}<180 \text{ deg} \qquad (9a)$$

and symmetrical about the longitudinal axis of the vessel, where

$C_{\mathrm{xyw}}\{\theta_{\mathrm{w}}\}$ =	normalized wind yaw moment coefficient
$a1$ =	negative peak value (from Table 25)
$a2$ =	positive peak value (from Table 25)
θ_{w} =	wind angle (degrees)
θ_{z} =	zero moment angle (degrees) (from Table 25)

$$\lambda = \frac{180 * \deg}{\left[(180 * \deg - \theta_z)\right]} \qquad \text{(dimensionless)} \qquad (9b)$$

Table 25
Normalized Wind Yaw Moment Variables

SHIP TYPE	Zero Moment Angle ($_z$)	Negative Peak (a1)	Positive Peak (a2)	NOTES
Liner	80	0.075	0.14	
Carrier	90	0.068	0.072	
Tanker	95	0.077	0.07	Center island w/ cluttered deck
Tanker	100	0.085	0.04	Center island w/ trim deck
Cruiser	90	0.064	0.05	
Destroyer	68	0.02	0.12	
Others:	130	0.13	0.025	stern superstructure
	102	0.096	0.029	aft midships superstructure
	90	0.1	0.1	midships superstructure
	75	0.03	0.05	forward midships superstructure
	105	0.18	0.12	bow superstructure

A plot of the yaw normalized moment coefficient for the example shown in Figure 30 is given as Figure 32.

Figure 32
Sample Yaw Normalized Moment Coefficient

4.5 Static Current Forces/Moments. Methods to determine static current forces and moments on stationary moored vessels in the surge and sway directions and yaw moment are presented in this section. These planar directions are of primary importance in many mooring designs.

4.5.1 Static Transverse Current Force. The transverse current force is defined as that component of force perpendicular to the vessel centerline. If a ship has a large underkeel clearance, then water can freely flow under the keel, as shown in Figure 33(a). If the underkeel clearance is small, as shown in Figure 33(b), then the ship more effectively blocks current flow, and the transverse current force on the ship increases. These effects are considered and the transverse current force is determined from the equation:

EQUATION: $$F_{yc} = 0.5\,\rho_w\,V_c^2\,L_{wL}\,T\,C_{yc}\sin\theta_c \qquad (10)$$

where

F_{yc} = transverse current force (newtons)
ρ_w = mass density of water (from Table 20)
V_c = current velocity (m/s)
L_{wL} = vessel waterline length (m)
T = average vessel draft (m)
C_{yc} = transverse current force drag coefficient
θ_c = current angle (degrees)

The transverse current force drag coefficient as formulated in Broadside Current Forces on Moored Ships, Seelig et al. (1992) is shown in Figure 34. This drag coefficient can be determined from:

Figure 33
Examples of Ratios of Ship Draft (T) to Water Depth (d)

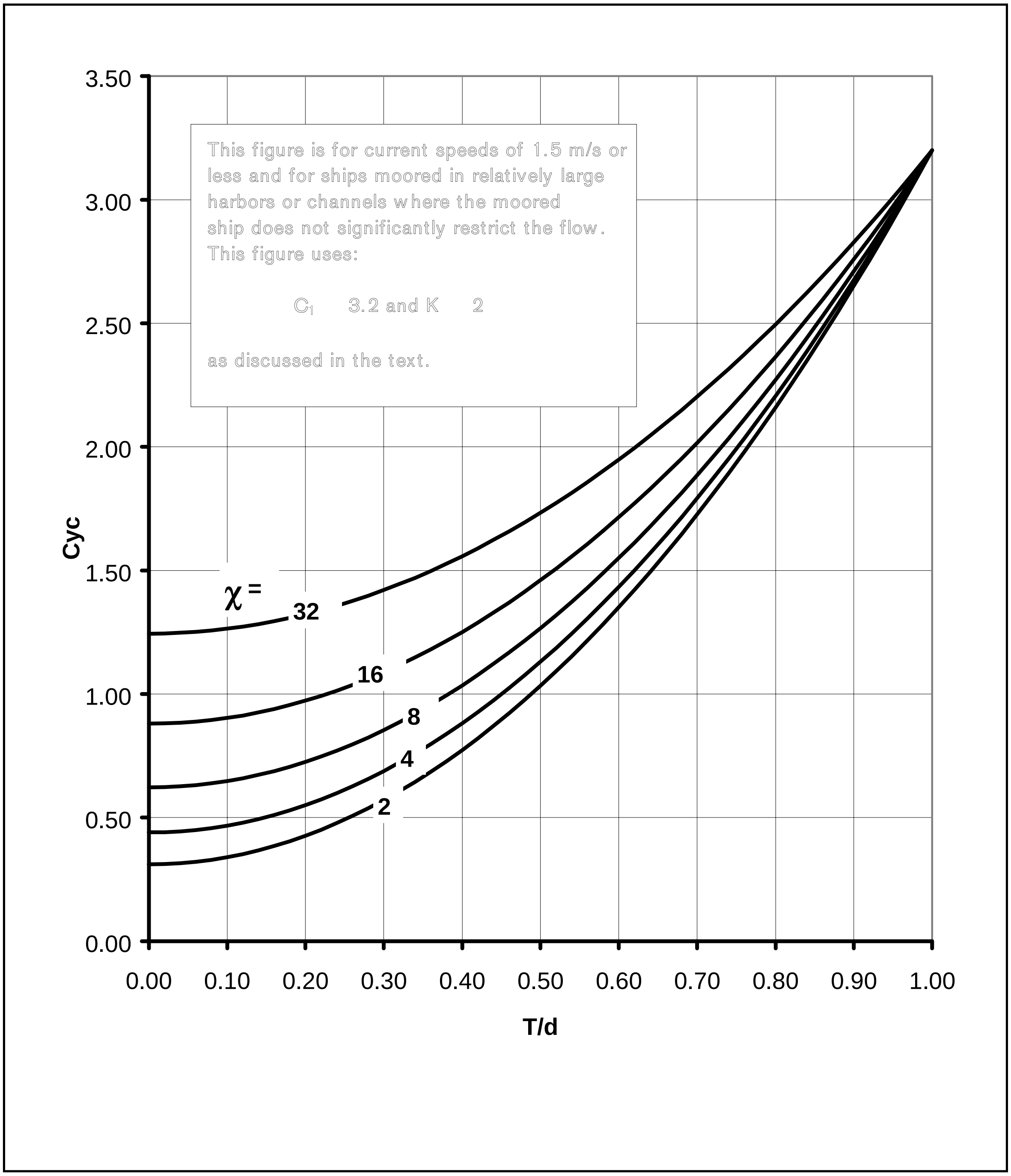


Figure 34
Broadside Current Drag Coefficient

EQUATION: $$C_{yc} = C_0 + (C_1 - C_0) * (T / d)^K \qquad (11)$$

where C_0 = deepwater current force drag coefficient for T/d 0.0; this deepwater drag coefficient is estimated from:

EQUATION: $$C_0 = 0.22 * \sqrt{\chi} \qquad (12)$$

where is a dimensionless ship parameter calculated as:

EQUATION: $$\chi = L_{wL}{}^2 * A_m / (B * V) \qquad (13)$$

where

L_{wL} is the vessel length at waterline(m)

A_m is the immersed cross-sectional area of the ship at midsection (m^2)

B is the beam (maximum ship width at the waterline) (m), and

V is the submerged volume of the ship (which can be found by taking the displacement of the vessel divided by the unit weight of water, given in Table 20 (m^3)).

C_1 = shallow water current force drag coefficient where T/d = 1.0; for currents of 1.5 m/s (3 knots or 5 ft/sec) or less

T = average vessel draft (m)

d = water depth (m)

K = dimensionless exponent; laboratory data from ship models shows:

K = 2	Wide range of ship and barge tests; most all of the physical model data available can be fit with this coefficient
K = 3	From a small number of tests on a fixed cargo ship and for a small number of tests on an old aircraft carrier, CVE-55
K = 5	From a small number of tests on an old submarine hull, SS-212

The immersed cross-sectional area of the ship at midships, A_m, can be determined from:

EQUATION: $$A_m = C_m * B * T \qquad (14)$$

Values of the midship coefficient, C_m, are provided in the NAVFAC Ship's Database for DOD ships.

The above methods for determining the transverse current force are recommended for normal design conditions with moderate current speeds of 1.5 m/s (3 knots or 5 ft/sec) or less and in relatively wide channels and harbors (see Seelig et al., 1992).

If the vessel is moored broadside in currents greater than 1.5 m/s (3 knots or 5 ft/sec), then scale model laboratory data show that there can be significant vessel heel/roll, which effectively increases the drag force on the vessel. In some model tests in shallow water and at high current speeds this effect was so pronounced that the model ship capsized. Mooring a vessel broadside in a high current should be avoided, if possible.

Scale physical model tests show that a vessel moored broadside in a restricted channel has increased current forces. This is because the vessel decreases the effective flow area of a restricted channel, which causes the current speed and current force to increase.

For specialized cases where:

(1) vessels are moored in current of 1.5 m/s (3 knots or 5 ft/sec) or more, and/or

(2) for vessels moored in restricted channels

then the designer should contact the Moorings Center of Expertise, NFESC ECDET, Washington Navy Yard Bldg. 218, 901 M St. SE, Washington DC 20374-5063.

EXAMPLE: Find the current force on an FFG-7 vessel produced by a current of $_c$=90 degrees to the ship centerline with a speed of 1.5 m/s (2.9 knots or 4.9 ft/sec) in salt water for a given ship draft. At the mooring location, the harbor has a cross-sectional area much larger than the submerged ship longitudinal area, $L_{wL} * T$.

SOLUTION: Dimensions and characteristics of this vessel are summarized in the lower right portion of Figure 35. Transverse current drag coefficients predicted using Equation 11 are shown on this figure as a solid bold line. Physical scale model data (U.S. Naval Academy (USNA), EW-9-90, <u>Evaluation of Viscous Damping Models for Single Point Mooring Simulation</u>) are shown as symbols in the drawing, showing that Equation 11 provides a reasonable estimate of drag coefficients. Predicted current forces for this example are given in Table 26.

Table 26
Predicted Transverse Current Forces on FFG-7
for a Current Speed of 1.5 m/s (2.9 knots)

T/d	d (m)	D (ft)	Fyc (MN)*	Fyc (kips)**
0.096	45.7	150	0.55	123
0.288	15.2	50	0.66	148
0.576	7.62	25	1.03	231
0.72	6.096	20	1.30	293
0.96	4.572	15	1.90	427

* MN = one million newtons
**kip = one thousand pounds force

This example shows that in shallow water the transverse current force can be three times or larger than in deep water for an FFG-7.

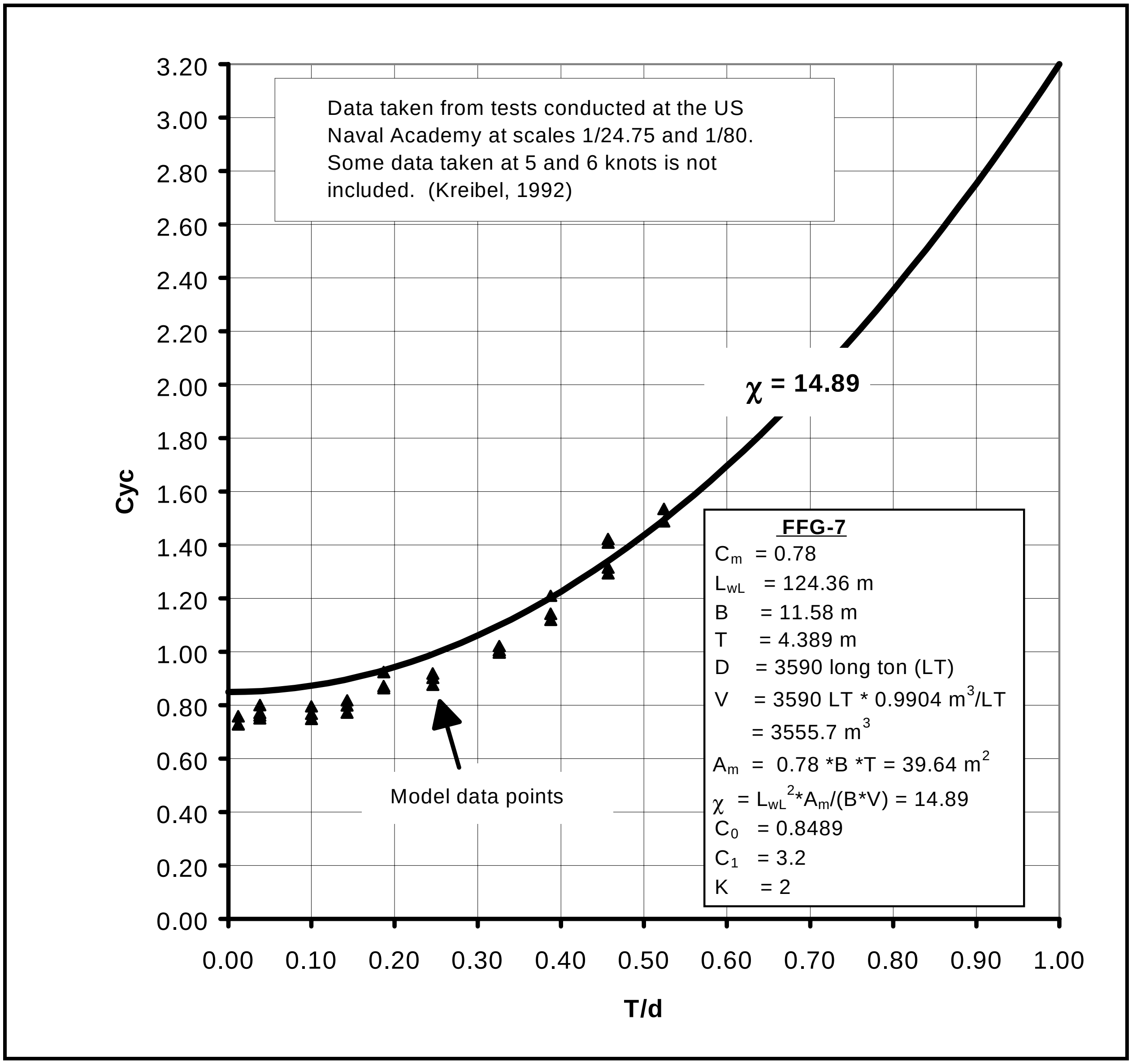


Figure 35
Example of Transverse Current Drag Coefficients

4.5.2 Static Longitudinal Current Force. The longitudinal current force is defined as that component of force parallel to the centerline of the vessel. This force is determined from the following equation (Naval Civil Engineering Laboratory (NCEL), TN-1634, STATMOOR – A Single-Point Mooring Static Analysis Program):

EQUATION: $$F_{xc} = F_{x\,FORM} + F_{x\,FRICTION} + F_{x\,PROP} \tag{15}$$

where

F_{xc} = total longitudinal current load (newtons)
F_{xFORM} = longitudinal current load due to form drag (newtons)
$F_{xFRICTION}$ = longitudinal current load due to skin friction (newtons)
F_{xPROP} = longitudinal current load due to propeller drag (newtons)

The three elements of the general longitudinal current load equation, F_{xFORM}, $F_{xFRICTION}$, and F_{xPROP} are described below:

F_{xFORM} = longitudinal current load due to form drag

EQUATION: $$F_{xFORM} = \frac{1}{2} \rho_w V_c^2 B T C_{xcb} \cos(\theta_c) \tag{16}$$

where

ρ_w = mass density of water, from Table 20
V_c = current speed (m/s)
B = maximum vessel width at the waterline(m)
T = average vessel draft (m)
C_{xcb} = longitudinal current form drag coefficient = 0.1
θ_c = current angle (degrees)

$F_{xFRICTION}$ = longitudinal current load due to skin friction

EQUATION: $$F_{xFRICTION} = \frac{1}{2} \rho_w V_c^2 S C_{xca} \cos(\theta_c) \tag{17}$$

where

ρ_w = mass density of water, from Table 20
V_c = current speed (m/s)
S = wetted surface area (m^2); estimated using

$$S = 1.7\ T\ L_{wL} + \left(\frac{D}{T\gamma_w} \right) \tag{18}$$

T = average vessel draft (m)
L_{wL} = waterline length of vessel (m)
D = ship displacement (newtons)
γ_w = weight density of water, from Table 21
C_{xca} = longitudinal skin friction coefficient, estimated using:

$$C_{xca} = 0.075 / \left(\left(\log_{10} R_N \right) - 2 \right)^2 \tag{19}$$

R_N = Reynolds Number

$$R_N = \left| \frac{V_c L_{wL} \cos(\theta_c)}{\nu} \right| \tag{20}$$

ν = kinematic viscosity of water, from Table 21
θ_c = current angle (degrees)

F_{xPROP} = longitudinal current load due to fixed propeller drag

EQUATION:

$$F_{xPROP} = \frac{1}{2} \rho_w\ V_c^2\ A_p\ C_{PROP}\ \cos(\theta_C) \tag{21}$$

where

ρ_w = mass density of water, from Table 21
V_c = current speed (m/s)
A_p = propeller expanded blade area (m^2)
C_{PROP} = propeller drag coefficient = 1.0
θ_C = current angle (degrees)

$$A_p = \frac{A_{Tpp}}{1.067 - 0.229\,(p/d)} = \frac{A_{Tpp}}{0.838} \qquad (22)$$

A_{Tpp} = total projected propeller area (m^2) for an assumed propeller pitch ratio of $p/d = 1.0$

$$A_{Tpp} = \frac{L_{wL}\,B}{A_R} \qquad (23)$$

A_R is a dimensionless area ratio for propellers. Typical values of this parameter for major vessel groups are given in Table 27.

Table 27
A_R for Major Vessel Groups

SHIP	AREA RATIO, A_R
Destroyer	100
Cruiser	160
Carrier	125
Cargo	240
Tanker	270
Submarine	125

Note that in these and all other engineering calculations discussed in this handbook, the user must be careful to keep units consistent.

EXAMPLE: Find the longitudinal current force with a bow-on current of $_{c}$=180 degrees with a current speed of 1.544 m/sec (3 knots) on a destroyer in salt water with the characteristics shown in Table 28.

SOLUTION: Table 29 shows the predicted current forces. Note that these forces are negative, since the bow-on current is in a negative “X” direction. For this destroyer, the force on the propeller is approximately two-thirds of the total longitudinal current force. For commercial ships, with relatively smaller propellers, form and friction drag produce a larger percentage of the current force.

Table 28
Example Destroyer

PARAMETER	SI SYSTEM	ENGLISH OR INCH-POUND SYSTEM
L_{wL}	161.2 m	529 ft
T	6.4 m	21 ft
B	16.76 m	55 ft
D, ship displacement	7.93E6 kg	7810 long tons
$C_{m;}$ estimated	0.83	0.83
S; est. from Eq 18	2963 m^2	31897 ft^2
A_R; from Table 27	100	100
R_N; from Eq 20	2.09E8	2.09E8
C_{xca}; est. from Eq 19	0.00188	0.00188
Ap; est. from Eq 22	32.256 m^2	347.2 ft^2

Table 29
Example Longitudinal Current Forces on a Destroyer

FORCE	SI SYSTEM	ENGLISH OR INCH-POUND SYSTEM	PERCENT OF TOTAL FORCE
F_{xFORM}; Eq 15	-13.1 kN*	-2.95 kip**	22%
$F_{xFRICTION}$; Eq 16	-6.8 kN	-1.53 kip	12%
F_{xPROP}; Eq 17	-39.4 kN	-8.87 kip	66%
Total F_{xc} =	-59.4 kN	-13.4 kip	100%

* kN = one thousand newtons
**kip = one thousand pounds force

4.5.3 Static Current Yaw Moment. The current yaw moment is defined as that component of moment acting about the vessel's vertical "Z"-axis. This moment is determined from the equation:

EQUATION: $$M_{xyc} = F_{yc}\left(\frac{e_c}{L_{wL}}\right)L_{wL} \qquad (24)$$

where

M_{xyc} = current yaw moment (newton*m)
F_{yc} = transverse current force (newton)
$\frac{e_c}{L_{wL}}$ = ratio of eccentricity to vessel waterline length
e_c = eccentricity of F_{yc} (m)
L_{wL} = vessel waterline length (m)

The dimensionless moment arm $\frac{e_c}{L_{wL}}$ is calculated by choosing the slope and y-intercept variables from Table 30 which are a function of the vessel hull. The dimensionless moment arm is dependent upon the current angle to the vessel, as shown in Equation 25:

EQUATION: $$\frac{e}{L_{wL}} = a + b * \theta_c \qquad _c\text{=0 to 180} \qquad (25)$$

$$\frac{e}{L_{wL}} = -a - (b * (360\,\text{deg} - \theta_c)) \qquad _c\text{=180 to 360} \qquad (25a)$$

where

$\frac{e_c}{L_{wL}}$ = ratio of eccentricity to vessel waterline length
a = y-intercept (refer to Table 30) (dimensionless)
b = slope per degree (refer to Table 29)
θ_c = current angle (degrees)

The above methods for determining the eccentricity ratio are recommended for normal design conditions with moderate current speeds of less than 1.5 m/s (3 knots or 5 ft/sec). Values provided in Table 30 are based upon least squares fit of scale model data taken for the case of ships with level keels. Data are not adequately available for evaluating the effect of trim on the current moment.

Table 30
Current Moment Eccentricity Ratio Variables

SHIP	a Y-INTERCEPT	b SLOPE PER DEGREE	NOTES
SERIES 60	-0.291	0.00353	Full hull form typical of cargo ships
FFG	-0.201	0.00221	“Rounded” hull typical of surface warships
CVE-55	-0.168	0.00189	Old attack aircraft carrier
SS-212	-0.244	0.00255	Old submarine

4.6 Wind and Current Forces and Moments on Multiple Ships. If ships are moored in close proximity to one another then the nearby ship(s) can influence the forces/moments on a given ship. The best information available on the effects of nearby ships are results from physical model tests, because the physical processes involved are highly complex. Appendix C provides scale model test results of wind and current forces and moments for multiple identical ships. From two to six identical ships were tested and the test results were compared with test results from a single ship. Data are provided for aircraft carriers, destroyers, cargo ships, and submarines.